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STEPS TOWARDS TERRAIN KNOWLEDGE ACQUISITION

Final Technical Report

by

Dr. Demetre P. Argialas

September 1995

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London England

Contract No: DAJA45-93-C-0015

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13. ABSTRACT (*Maximum 200 words*)

In all previous approaches of the author and others in constructing prototype expert systems for landform interpretation,(1) knowledge related to the physiography of a site was expressed indirectly through *a priori* conditional probabilities of the occurrence of each landform in each physiographic section, (2) only a limited number of pattern elements were used, (3) there was no use of geomorphic process rules, (4) there was no use of regional context, (5) the systems processed only one landform at a time, and (6) there was no backward reasoning capability available. In this effort it has been developed a new conceptual scheme which was formalized through objects and rules so that to permit representation of (1) physiographic region reasoning, (2) an expanded (more detailed) set of pattern elements, (3) geomorphic process reasoning, (4) regional context (spatial) reasoning, (5) multiple landform instances at a given interpretive scenario, (6) both forward and backward reasoning. The presented case studies concern typical terrain of the Basin and Range Province of Southwest USA. Detailed, "book-level" knowledge pertaining to landforms and physiographic regions was gathered in the form of tables. The knowledge-base contains object and class representations of the typical landforms of the Basin and Range province such as alluvial fans, valley fills and playas as well as the typical physiographic regions of the province.

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TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This report is the result of an investigation entitled "Steps Towards Terrain Knowledge Acquisition" which was conducted for the U.S. Army Topographic Engineering Center (TEC), 2592 Leaf Road, Fort Belvoir, VA 22060-5546, through the European Research Office of the U.S. Army, under Contract No. DAJA45-93-C-0015, R&D No: 6958-EN 09.

The work was performed by Dr. Demetre P. Argialas of 28 Mithimnis St. Athens, Greece, under the Scientific Liaison of Dr. George Lukes - USATEC.. Technical Representative of the European Research Office, London, UK was Mr. Jerry C. Comati, Chief Environmental Sciences Branch.

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1. Introduction

Terrain analysis is the systematic study of image elements relating to the nature, origin, morphologic history and composition of distinct units called landforms (Way 1978, Lillesand and Kiefer 1979, Mintzer 1983, Mintzer and Messmore 1984). *Landforms* are natural terrain units, usually of the third relief order, which when developed under similar conditions of climate, weathering, and erosion exhibit a distinct and predictable range of visual and physical characteristics. The entity of landform is fundamental in representing and organizing topographic and geomorphic information through the pattern-element approach to terrain analysis. The *landform-pattern element approach* is based on the following premise: any two terrain surfaces derived from the same soil and bedrock, or created by a similar process, occupying the same relative position, and existing under the same climatic conditions exhibit similar physical and visual features on aerial images, called *pattern elements* (Way 1978, Lillesand and Kiefer 1979, Mintzer 1983, Mintzer and Messmore 1984). The elements examined include topographic form, drainage pattern, gully characteristics, soil tone variation and texture, land use, vegetation, and special features (Table 1). An analysis of the meanings of some of these generic topographic-terms has been published by Rinker and Corl (1984), Hoffman (1985) and Hoffman and Pike (1993).

Table 1 Some landform-pattern elements and their types.

Topographic form	**Drainage pattern**	**Vegetation-land use**	**Special feature**
A-shaped hill	Anastomotic	Barren	Blowouts
Bold domelike hill	Angular	Cultivated	Cigar-shaped
Broad and level plain	Annular	Forested	Columnar jointing
Conical hill	Asymmetrical	Grass	Contour farming
Crescent-shaped hill	Barbed	Natural cover	Fan-shaped
Dissected plain	Braided	Rangeland	Fluvial marks
Drumlin shaped	Centripetal	Urban	Hummocky slopes
Fan-Shaped plain	Collinear	Wetland	Meanders
Flat	Contorted		Natural levees
Flat table rocks	Dendritic		Parallel ridges
Gently rolling	Deranged		Rounded boulders
Hill	Dichotomic		
Hummock	Elongated bay		
Isolated hill	Illusory		
Karst	Incipient		
Level plain	Internal		
Massive hill	Kettle hole		
Parallel laminations	None	**Gully shape**	
Parallel ridges	Parallel	U-shaped	
Pitted plain	Pinnate	V-shaped	
Plain	Radial	White fringed	
Ridge	Rectangular		
Ridge and Plain	Reticular		
Rounded Hill	Subdendritic	**Soil tone variation**	
Saw-toothed ridge	Subparallel	Black	
Sinkhole	Swallow hole	Dull gray	
Snakelike ridge	Thermokarst	Light gray	
Soft Hills	Trellis	White	
Soft rounded hill	Yazoo		
Star-shaped hill		**Soil tone texture**	
Steep Hillsides		Banded	
Undulating plain		Mottled	
Vertical slopes		Scrabbled	
Kettle-knob		Uniform	

Terrain analysts use the pattern elements, as well as maps and bibliographic information, to identify landforms, their parent material, and their engineering characteristics and significance. The landform is inferred from the pattern-elements of the site and then the parent material is inferred by its association with the landform. The discipline was developed by terrain analysts who used image analysis as a source for terrain information for operations planning and construction projects (Way 1978, Lillesand and Kiefer 1979, Mintzer and Messmore 1984).

Problem solving. in this approach commences with the analyst formulating hypotheses about the landforms likely to occur in the study area, by drawing upon his experience and auxiliary information specific to the region (Mintzer and Messmore 1984). Then he searches the aerial image, to find a match between the expected pattern elements of one of the hypothesized landforms - as those are found in texts and guides - and the observed characteristics. The analyst continues this procedure, until all the pattern elements are examined. If there is a significant match between the expected and observed pattern elements, the identity of the landform of the site is established. Otherwise, the next landform in the hypothesis list is investigated for a match.

1.1 The need for computational models for landform interpretation

Terrain analysis can be time consuming, labor intensive and costly. Its skills are a product of lengthy and expensive training. Therefore, it could help to at least partially automate this process by developing computer-assisted interactive systems. Such systems could improve training by introducing students to the decisions made by experts and by improving the quality and reliability of interpretation. At the same time provide a research vehicle to explore and test the landform-related knowledge.

Landform interpretation is still an art without a formal theory (Ryerson 1989, Hoffman 1987). Knowledge, available in books, is descriptive and fuzzy. A procedural framework for problem solving is missing: books do not elaborate on the strategies needed to guide a novice to the process required for landform identification. On the other hand, trained and skilled experts routinely perform landform interpretation. Implicit terrain-related knowledge, somehow enables the expert to directly perceive or indirectly infer landforms from aerial images. Expertise is not documented in textbooks and manuals and hence it is not clear, explicit and unambiguous. It can not be easily taught, expanded, preserved, transferred, replicated, and criticized.

There is, therefore, a need to methodically study the terrain-analysis reasoning process and, to better understand this process, develop a systematic framework for the recognition of landforms from aerial images (Leighty 1973 and 1979, Hoffman 1985, Argialas and Narasimhan 1988a and 1988b). Knowledge-based expert systems offer the promise for the representation of data and reasoning in many fields including image interpretation.

1.2 Knowledge-based expert systems

Knowledge-based expert-systems (KBES) are a field of artificial intelligence that addresses complex, domain specific, problem solving that requires unique expertise (Hayes-Roth et al. 1983, Harmon and King 1985, Jackson 1986). Their performance depends critically on facts and heuristics used by experts. Their success is largely determined by the effective computer representation of domain knowledge.

Production rule-based systems are the most widely used scheme for knowledge representation. *Factual knowledge* is represented as object-attribute-value triples. *Strategic knowledge* is represented as sets of *rules*, of the form IF ["condition statements"] THEN ["action statements"], that will be checked against a collection of problem *facts* to infer new facts. When a problem satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed. The execution of a set of rules, commonly called *rule-chaining*, results in a new set of facts which is added to the existing list, which trigger other rules. In such a system rules can operate in forward or backward chaining. *Forward chaining* matches rules against facts to establish new facts. In *backward chaining*, the system starts with what it wants to prove and tries to establish the facts it needs to prove it.

Frames, another knowledge-representation scheme, are structural models for representing stereotyped objects or situations (Minsky 1975). A *class frame* is a collection of all information that describes a class

of objects. An *object* or *instance frame* is a collection of all information that describes an individual of a class frame. Each frame has *slots* that contain properties and relations about classes and objects. The slots specify, through an associated set of rules or procedures, what is known about an object and how can be acquired. *Inexact reasoning procedures* have been developed to complement the knowledge representation and inferencing mechanisms of rule and frame based systems in case where facts, rules and, consequently, conclusions are uncertain or inexact. These techniques represent *uncertainties* in facts, combination of facts, rules of inferencing, and facts supported independently by several rules (Harmon and King 1985, Jackson 1986).

1.3 Knowledge-based expert systems for landform interpretation

Towards the methodical representation of data and of reasoning in landform interpretation Argialas and his associates used a variety of expert-system methods and tools to address terrain knowledge-representation through the landform-pattern element approach and to construct prototype expert-systems for inferring the landform of a site from user observations of pattern elements. Meanwhile others also developed pertinent methods and knowledge bases including Leighty (1973, 1979), Rinker and Corl (1984), Mintzer (1988), and Edwards (1987).

The expert-system approach to terrain-analysis problem-solving was first implemented in a rule-based production system language involving inexact reasoning (Argialas and Narasimhan 1988a and 1988b). Subsequent work added such knowledge-representation formalisms as frames (Argialas 1989) and fuzzy sets (Narasimhan and Argialas 1989). The systems described were called Terrain Analysis eXperts (TAX-1, 2, 3) (Table 2).

Table 2 Comparative features of the three terrain analysis expert-system prototypes.

Feature of prototype	TAX-1	TAX-2	TAX-3
Object representation	Object-attribute-value	Frames	Frames, objects
Inference	Production rules	Rules	Rules, demons
Inexact reasoning	Bayesian	Bayesian	Fuzzy sets
Rule chaining	Forward	Backward/forward	Backward/forward
Expert system tool	OPS5	INTELLIGENT COMPILER	KEE

In TAX-1 *factual knowledge* described the landforms in relation to their pattern elements and the physiographic sections in relation to their expected landforms (Table 3). *Strategic knowledge* (problem-solving decisions) were represented by inexact production rules through a Bayesian formalism (Tables 4, 5). Based on user response for the query of the physiographic section of the site, the system constructed a set of candidate landforms of the site and estimated their *a priori* probabilities. TAX then chose the landforms in this candidate list, one by one, and attempted to establish each one of them, by matching the user-supplied pattern-elements of the site with those expected.

Table 3 Probabilities of occurrence of three landforms in the physiographic section Cumberland Plateau as used in the TAX-1 expert system

Physiographic Section	Landform type	Probability of occurrence
Cumberland Plateau	Humid sandstone	0.45
Cumberland Plateau	Humid shale	0.45
Cumberland Plateau	Humid limestone	0.10

Table 4 Typical landform-related objects with their attributes and values designed for the TAX-1 expert system shown coded in the OPS5 language and explained in English. Objects are shown boldface, attributes are preceeded by a caret, and values are shown in italics.

landform_topography_pair

^landform_type	*sandstone_humid*
^topography	*steep_slopes*
^landform_topography_peh	*0.60*
^landform_topography_penoth	*0.0*
^status	*nil*

This object was designed to express the relation between any landform and its topography. This instance of this object indicates that landform "sandstone_humid" has topography "steep_slopes" with probability - P(E/H)=0.6 and it has not been used for reasoning as yet by TAX (status=nil).

landform_of_the_site

^landform_type	*sandstone_humid*
^probability	*0.45*
^status	*nil*

This object was designed to store the *a priori* or *a posteriori* probability of any landform of the site. The initial value, here set to 0.45, is obtained from *a priori* knolwedge regarding the site. This instance of this object indicates that landform "sandstone_humid" has *a priori* probability - P(H)=0.45 and it has not been used for reasoning as yet by TAX (status=nil).

topography_of_the_site

^landform_type	*sandstone_humid*
^topography	*steep_slopes*
^certainty_value_of_topography	*+1*
^status	*nil*

This object was designed to store the topography of the site and its certainty - as these are provided by the user. This instance of this object indicates that topography "steep_slopes" was observed by the user with certainty +1 and landform "sandstone_humid" is one of the canditate landforms with such topography. Similar objects will also be created for all other landforms of the knowledge base which are known to have topography "steep_slopes".

A second prototype, the Terrain Analysis Expert-2 (TAX-2) system (Argialas 1989) was designed in the Intelligence Compiler, a frame and rule based expert-system tool (Intelligence Ware 1986). Table 2 shows the comparative features of the three implementations of TAX-1, -2, -3. TAX-2 demonstrates the representation and reasoning capabilities of frames, backward and forward chaining rules, and inexact reasoning for the landform interpretation. Frames were developed to represent relations between physiographic sections and landforms, landforms and their pattern elements, and pattern elements and their associated likelihood of occurrence in each landform type. Frames demonstrated the *inheritance* of attributes from generic representations of terrain units to their specific instances. Frames also represented procedural knowledge by embedding it in the form of *active values* or *attached predicates*. Fig. 6 shows a typical frame for *topography*. It is indicated, through the property *parent*, that frame *topography* is a child of frame *pattern-element-generic*. *Topography* has been designed with ten slots (properties), some declare possible values (e.g., *steep-slopes*, *medium-slopes*, and *flat-undulating*), others declare default assignments (e.g., *name*). while others contain specific values or have attached predicates for computation of values (e.g., *best*). Property *best* has a procedural attachment, e.g. predicate *get-inferred*, which will call the corresponding backward rule.

Table 5 Rule that hypothesizes a landform type based on physiographic information designed for the TAX-1 expert system shown coded in the OPS5 language and explained in English.

OPS5 coded rule	(p hypothesize_a_landform_type_based_on_physiogrphy (section_landform_pair ^section_name <section_value> ^landform_type <landform_value> ^section_landform_prob <probability_value> -> (make landform_of_the_site ^landform_type <landform_value> ^probability <probability_value>))	
Explanation of OPS5 language symbols	**p**	means that what follows is a production rule
	^	implies that what follows is an attribute name
	<>	encloses an attribute value
	->	means "then"
English version of above rule	If	there exists a landform type in the knowledge base which occurs in the same physiographic section as the one given by the user,
	then	create an object landform-of-the-site and initialize its probability to the a priori probability of the occurrence of that landform type in that physiographic section

Table 6. A frame for Topography with attributes and attached procedures

Frame	**Topography**	
Parent	Pattern element generic	
Best		get-inferred
Name	Topography	
Steep_slopes	SS	ask_value
Medium_slopes	MS	ask_value
Flat_undulating	FU	ask_value
Sandstone	Sandstone_topography-eh	
Shale	Shale_topography-eh	
Limestone	Limestone-topography-eh	

A third prototype, the Terrain Analysis Expert-3 (TAX-3) system (Table 2) was designed so that to represent the vagueness and imprecision that is inherent in the qualitative descriptions of terrain terms by fuzzy sets (Narasimhan and Argialas 1988b, Narasimhan and Argialas 1989). *Fuzzy set* approaches, pioneered by Zadeh (1983) provide a way for dealing with vague linguistic descriptions such as "gentle relief", and "partly dendritic, partly rectangular drainage pattern".

A typical consultation script generated with the terrain analysis expert system TAX-1 is shown in Table 7.

Table 7 A typical consultation script generated with the terrain analysis expert system TAX-1. Underscored and boldfaced numbers indicate the user's certainty, between -3 and 3, for the presence of the specific pattern-element value in the study area.

Please provide the following information about the site.
To which Physiographic-section does the site belong?
Cumberland-plateau
Is the "gully-amount" of the site "none" ? **- 3**
Is the "gully-amount" of the site "few" ? **1**
Is the "gully-type" of the site "v-shaped" ? **3**
Is the "landuse-valleys" of the site "cultivated" ? **- 1**
Is the "landuse-valleys" of the site "forested" ? **3**
Is the "landuse-slopes" of the site "cultivated" ? **- 3**
Is the "landuse-slopes" of the site "forested" ? **3**
Is the "soil-tone" of the site "medium" ? **1**
Is the "soil-tone" of the site "light" ? **0**
Is the "soil-tone" of the site "dark" ? **0**
Is the "drainage-texture" of the site "coarse" ? **3**
Is the "drainage-type" of the site "internal" ? **- 2**
Is the "drainage-type" of the site "angular" ? **2**
Is the "topography" of the site "steep-slopes" ? **3**
Is the "gully-amount" of the site "many" ? **- 2**
The site appears to be "sandstone-humid"
The certainty associated with this result is "0.99"

Parallel to these efforts, Argialas (1991, 1995) developed a visual vocabulary of pattern-elements through a Macintosh-based hypermedia system consisting of interlinked definitions, graphics, and aerial images which can be browsed in a non-linear, non-sequential, user-defined manner and which can be use simultaneously with an expert consultation system. The prototype Terrain Visual Vocabulary (VVT) system was designed to include three components to define and graphically depict landform features: (1) definitions, (2) diagrams (line drawings), and (3) scanned aerial images. The system was built in Hypercard, the *authoring software environment* of the Apple Macintosh computer (HyperCard Stack Design Guidelines 1989). The potential of hypermedia for structuring the relevant knowledge for training in image interpretation was described in Argialas and Mintzer (1992).

2. Problem Identification

The approach for building the Terrain Analysis eXpert systems (TAX-1, 2, 3, 4) involved development of five interdependent and overlapping tasks: (1) *Identification,* (2) *Conceptualization,* (3) *Formalization,* (4) *Implementation,* and (5) *Testing* and *evaluation.*

Identification pertains to data, hypothesis, goals, and reasoning tasks of TAX.

The goal of a typical consulting session with TAX 1, 2, 3

- was to infer the landform type of a site, assuming that one landform type was shown on a stereopair of aerial photographs,
- the conceptual scheme for the recognition of the landforms was the landform pattern-element approach, described earlier,
- the association between physiographic sections and their expected landform types were described with the use of probabilities expressing the occurrence of each landform in the corresponding physiographic section,
- six landform types were chosen to focus the knowledge-representation process, the humid and arid forms of sandstone, shale and limestone,
- the domain knowledge was composed of facts collected from (1) books (Way 1978, Lillesand and Kiefer 1979), (2) reports (Mintzer and Messmore 1984), (3) the experience of the authors, and (4) an interview with an expert terrain analyst.

While TAX-1, 2 has demonstrated the use of *a priori* physiographic information for focusing the search for the identification of the landform of the site, the expert analyst would better take into account the physiographic context, the regional context, the geomorphic process and other information to arrive at a diagnosis of the landform. With such "deeper knowledge" taken into account, the landform expert systems would be able to reason much beyond the pattern elements alone. Therefore there is a need to study such additional contexts.

Furthermore, the traditional pattern elements only hint at what the expert perceives (Hoffman 1987). Therefore, the use of pattern elements as the means for identifying the landform is a "zero order approximation" to how experts work during landform identification and as such it is limited. It has contributed to the first-generation prototype expert-systems for terrain analysis. To build the next generation of systems, which could successfully handle additional aspects of problem solving, it is necessary to create new conceptualization schemes to more explicitly represent additional aspects of landform identification.

TAX was designed based on a Bayesian decision network created through forward and backward chaining inference engines coupled with objects or frames. It will be unfair though to assume that humans think (only) in terms of probabilities, certainties or membership functions. The hiding of perceptual relativity in numbers is merely a brute force solution to the tough problem of perception. The systems may work (more or less well) but in some sense, it washes the "meaning" away (Hoffman 1987). One has to uncover the knowledge hidden beneath the probabilities and certainties during reasoning and make that knowledge explicit with rules etc. It is evident therefore that in order to increase the granularity level of the represented knowledge in order to create smarter applications.

These concerns have urge us in pursuing the present research effort. In the present effort, TAX-4, the goals of a typical consulting session were set as following:

- to infer the landform type of a site by using an expanded set of pattern elements,
- to infer the landform type of a site by using regional context information,

- to infer the landform type of site by using geomorphic process context in addition to the pattern elements,
- to infer the physiographic region (province, section) of a site by using physiographic site indicators,
- to infer more that one type of landforms at any given consultation session,
- to perform some of the above inferences in a backward and forward mode of reasoning, and
- the landforms being considered for the knowledge-representation process are those that are common to the Basin and Range Province (alluvial fans, pediments, playas, valley fills).

Conceptualization and *formalization* involve the representation of factual and strategic knowledge in appropriate knowledge structures. In TAX-1, 2, 3 the factual and strategic knowledge were represented as described earlier and in the corresponding papers in more detail (Argialas 1995).

In TAX-4, the present effort, the conceptualization and formalization schemes involved the representation of factual and strategic knowledge in appropriate knowledge structures as these are described in the next section.

Conceptualization and formalization of

3. Conceptualization and formalization of a landform interpretation knowledge base for the Terrain Analysis eXpert - 4 (TAX-4)

A knowledge-based expert system is composed mainly of an inference engine and a knowledge-base. The inference engine is usually embedded within the expert system tool that is used for building the knowledge base.

A knowledge-base is composed of data representation (factual knowledge) component and a reasoning component. The data representation component has evolved from object-attribute-value triplets to object-frame representation. The reasoning component has evolved from production rules to integrated rule-and-frame formalisms which present certain advantages for knowledge representation. In between, there are the predicate logic systems. Meanwhile, reasoning may be achieved by either forward chaining rules, backward chaining rules, or bidirectional rules. In either case, reasoning is creating what often is called an inference chain. These knowledge representation formalisms have been developed into expert system tools (Intelligence Compiler, KEE, Nexpert Object, CLIPS).

The developed formalism for the present knowledge representation effort for landform interpretation relies on a rule-based and frame-based formalisms, and consequently, its implementation assumes a frame- and rule-based expert system tool, where rules could be invoked in a forward or backward chaining method.

Such tools which have the ability to support both a rule-based reasoning system and an object-oriented representation are called hybrid expert system tools. Examples of the developed landform representation formalism will be given in such hybrid expert systems tools, although the representation is independent of any specific tool.

3.1 Landform-related object structures

To represent real world data and their properties (factual knowledge) in an expert system pertaining to landform interpretation it is necessary to use data representation structures that are stored in the knowledge base as class frames, subclass frames, object frames, subobjects frames, and slots.

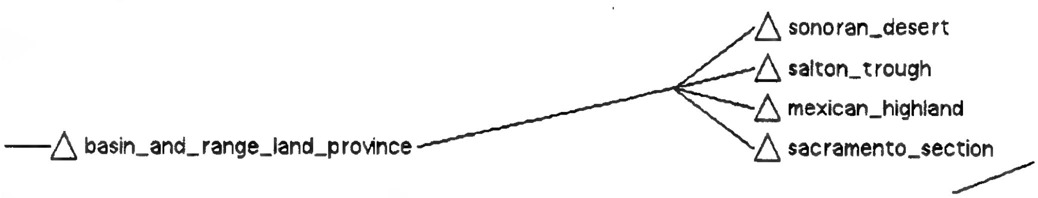
3.1.1 Objects and sub-objects.

An object is an elementary unit of description. Anything can be an object:

- Objects represent the knowledge being reasoned on by the rules.

- Objects describe variables in the knowledge base.

Objects can include sub-objects if additional levels are needed to define unique characteristics. For example, the object "Basin and Range land province" contains the sub objects Sonoran desert, Salton Trough, Mexican Highland, etc. that possess characteristics in addition to those of the parent object (Figure 1).



NAME : basin_and_range_land_province
CLASSES :
    land_province
SUBOBJECTS :
    great_basin
    sonoran_desert
    salton_trough
    mexican_highland
    sacramento_section

Figure 1. Objects and subobjects for physiographic provinces and sections

3.1.2 Classes.

A class is a collection of objects that usually share properties. Functionally, classes act as a template that defines the characteristics its members must possess.

For the landform identification problem, it is appropriate to design various classes from which the landform instances of a site will inherit various properties. From this point of view one may design classes for the various geomorphic processes, the climate, the types of landforms, etc. (Figure 4 to Figure 7).

Objects and subclasses can obtain their characteristics dynamically from a particular class through a mechanism called inheritance.

3.1.3 Class-instances (members)

Descriptive information is expressed in class-member relationships that are stored in the knowledge base. The members of a class are its objects and are typically referred to as "instances of a class."

Assuming that we have created a number of pertinent classes to describe landforms and their associated concepts, we need to make a good use of them by assigning the proper members/instances of each class. One particular use of the instances of a class is made for representing the landforms interpreted for a site. For example, when a new interpretation is a made of an alluvial fan landform, then that landform is made to be an instance, designated as af_1, of the class of alluvial landform landforms. If a second alluvial fan landform is being recognized then it takes the designation af_2 and it is considered an instance of the same class. If a playa is recognized then it is designated as pl_1, etc. and it is considered a member of the class of playas.

Implicit in this formalization of the landform interpretation process, is that at any interpretive scenario we may need:

- to recognize more than one landforms at a given time and also

- to be able to exploit the spatial relations among the recognized landforms which is useful for establishing the regional context.

Figure 2 shows a simple case of a superclass "landform generic" that contains the class of alluvial fan, which has been assigned the instance af1 which was recognized as an alluvial fan. Obviously the properties of landform_generic are inherited in the class alluvial fan, and the properties of the later are inherited to those of the instance af1. Figure 3 shows the same scenario of instance creation for two interpreted landforms: af_1 and pl_1.

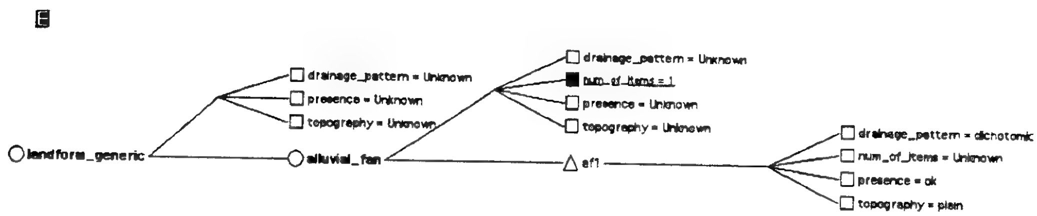


Figure 2: Dynamic object (af1): instance of a landform class created during the expert system consultation

Figure 3. Dynamic objects (af_1, pl_1): instances of two landform classes created during the expert system consultation

3.1.4 Class-subclass relationships and inheritance

Classes can include sub-classes if additional levels are needed to define unique characteristics. Such taxonomic information is expressed as class-subclass relationships. Describing classes through subclasses gives access to a hierarchical representation of objects.

It is constructive, while building a knowledge base, to try to partition (compartmentalize) the knowledge base into as small chunks of knowledge as possible. This is true for both objects (classes) and rules. Toward this goal, and while an effort has been made to add geomorphic, regional, and physiographic context into the knowledge base, it was also attempted the compartmentalization of the pertinent classes. Figure 4 shows a hierarchical taxonomy of geomorphic processes in three levels. The property (geomorphic agent) is shown to be inherited but with different values for each geomorphic process. Figure 5 shows in larger font a segment of this hierarchy. It should be emphasized that the alluvial fan landform class is a subclass of fluvial erosion landforms, with the value of agent being water. Besides the property "agent" there are other properties that may also be inherited down the tree.

Figure 6 shows a topographic hierarchy where the mountains of the Basin and Range Province are a kind of tilted blocks and the Basin Floor is a kind of Plain. Figure 7 is class hierarchy of climate.

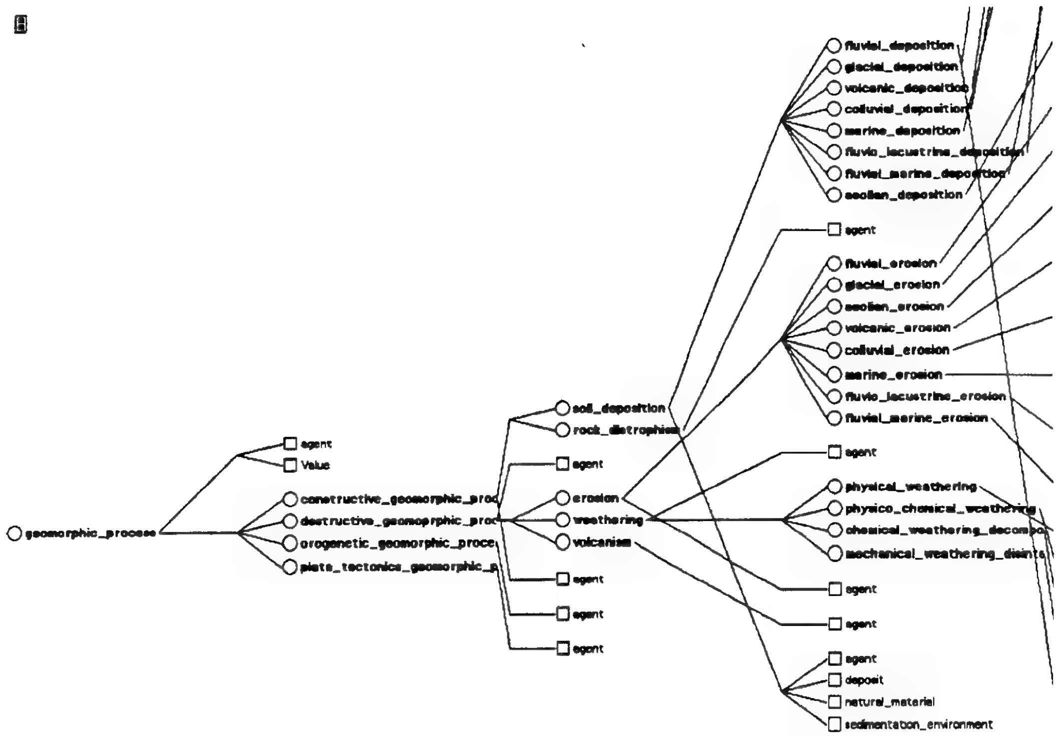


Figure 4. A hierarchical taxonomy of geomorphic processes in three levels

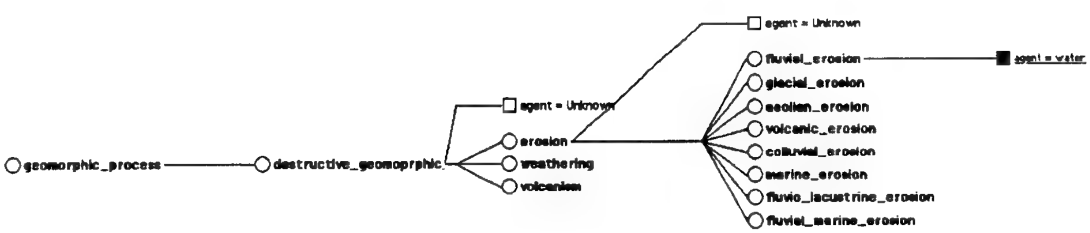


Figure 5. A partial hierarchical taxonomy of geomorphic processes in three levels

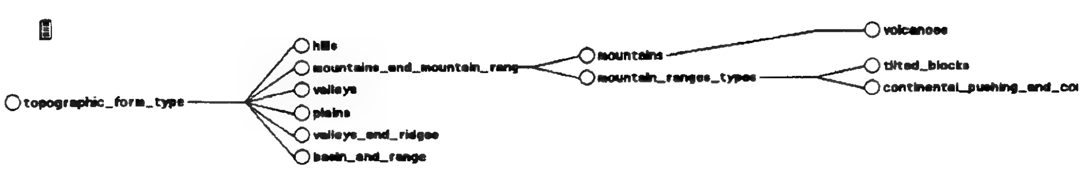


Figure 6. A partial topographic hierarchy

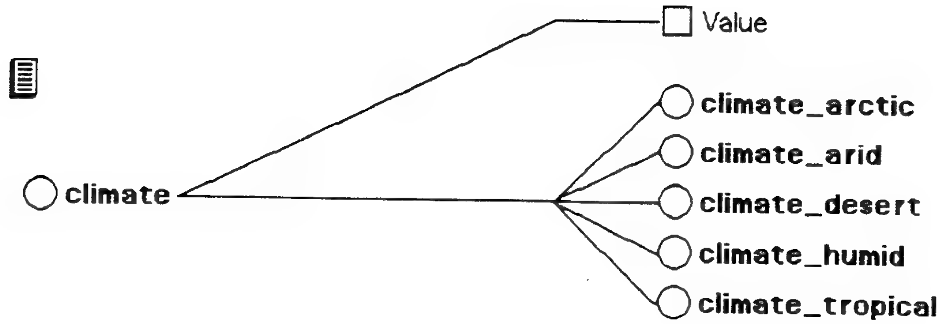


Figure 7. Climatic classes

3.1.5 Class and object properties (slots)

A property is a characteristic which can be associated with an object or a class. The characteristics of an object are its properties. A particular property when associated with an object is called a slot. A slot in the knowledge base is a variable written as ObjName.PropName that has some value. For example, the slot landform.drainage_pattern might be Unknown or if Known, dichotomic.

Most of the figures (Figure 2 to Figure 7) shown earlier to demonstrate class/subclass taxonomies contained properties attached as slots from the objects and classes. Figure 8 contains a very large number of properties for the object landform generic (not shown). These properties are inherited in the instances and subclasses of the landform_generic class.

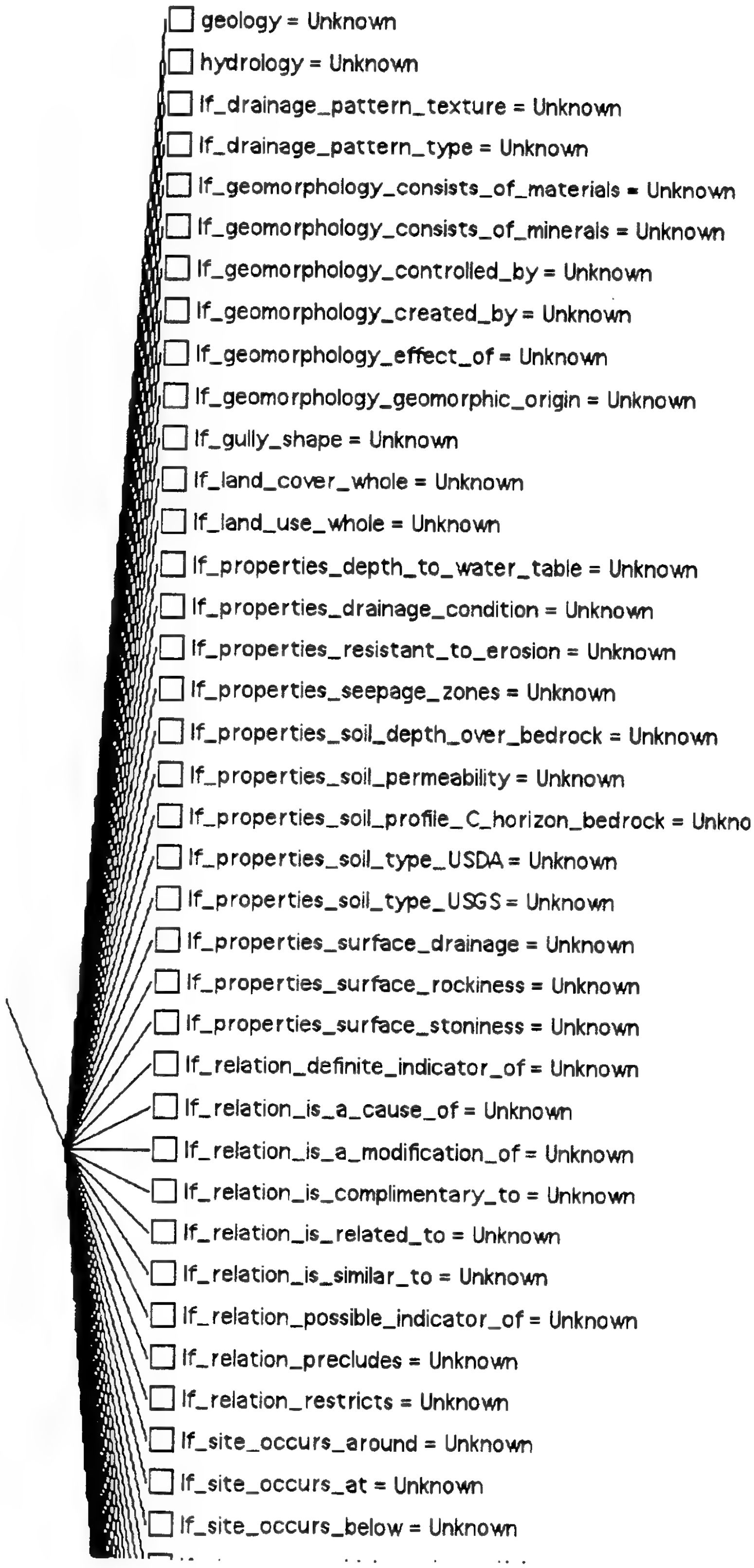


Figure 8. Partial properties of the class landform_generic

3.2 Rule structure and rule evaluation

To represent reasoning in an expert system pertaining to landform interpretation it is necessary to use situation-action statements that are stored in the knowledge base as rules.

A **rule** is a chunk of knowledge representing a situation, usually an interpretation scenario, and its immediate consequences. The format of a rule is expressed as:

if ... then ... and do...

The "if" is followed by a set of conditions, the "then" by a hypothesis or goal which becomes true when the conditions are met, and the "do" by a set of actions to be undertaken as a result of a positive evaluation of the rule.

Therefore, a rule has three parts. The first part, comprised of one more If-clauses, gives verifiable conditions/evidences that must apply if the second part, comprised of a hypothesis (conclusion), and the third part, comprised of one more do-clauses, are to be triggered by the inference engine. The "if" and "do" parts of a rule may contain actions the system initiates.

The hypothesis is the particular name assigned to the conclusion of one or more rules. For example, the hypothesis name H_alluvial_fan_surface_morphology is being assigned to the rule in Figure 9 which is used to identify an alluvial fan from its pattern elements. The inference engine attempts to conclude a boolean value for the rule's hypothesis through the evaluation process. The outcome of rule evaluation can result in a hypothesis receiving the value True, or False.

In Figure 9 the list of tests in the left part is the Left-Hand Side (LHS) of the rule. It is where the conditions are expressed and tested. In the same part there are a number of actions indicated and preceeded by the ==> symbol. The Right-Hand Side (RHS) of the rule contains the hypothesis name h_alluvial_fan_surface_morphology and the actions previously explained.

When the rule is found to be true, the RHS actions are triggered. They are called actions because they induce some change in the overall system or its environment. Figure 10 illustrates the types of actions that can occur when a rule is fired:

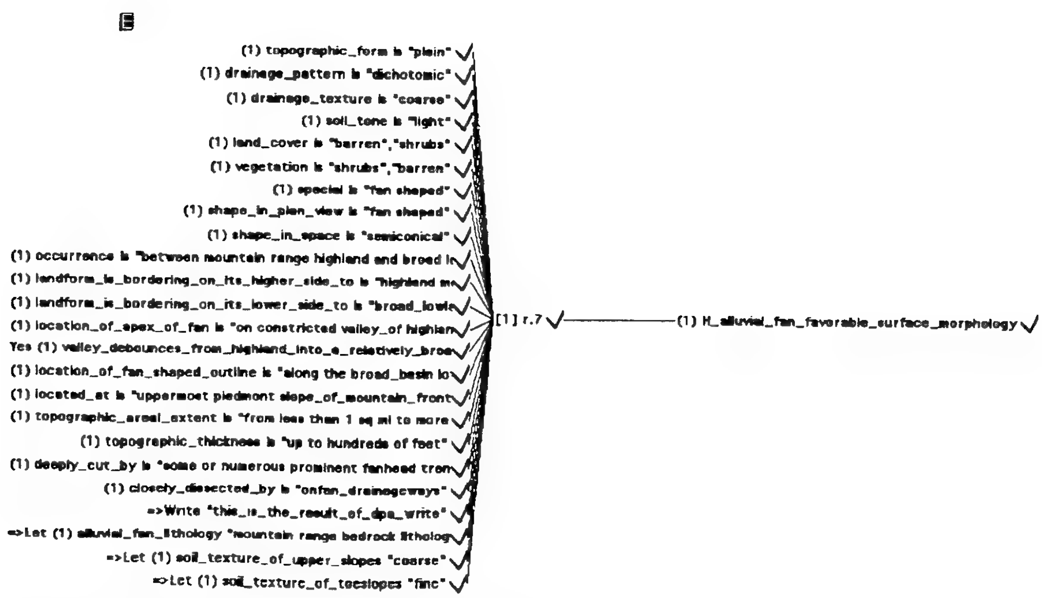


Figure 9. The components of a rule for the hypothesis H_alluvial_faforable_surface_morphology

```
LIST OF RULES

                         Rule 15
If   Execute "Message"(@STRING="@TEXT=I am trying to establish the hypothesis of alluvial fan,
  And Execute "Message"(@STRING="@TEXT=Now entering rule alluvial fan,@OK";)
  And topography is "plain"
  And drainage_pattern is "dichotomic"
Then h_alluvial_fan
  is confirmed.
  And Create Object af1 |alluvial_fan|
  And af1.topography is set to "plain"
  And af1.drainage_pattern is set to "dichotomic"
  And af1.presence is set to "ok"
  And Reset topography
  And Reset drainage_pattern
```

Figure 10. Possible actions initiated in rule evaluation: creation of an alluvial fan instance of the class of alluvial fans and allocation of values to its slots, based on user input. Resetting is a house cleaning routine.

3.2.1 Single rule evaluation (backward and forward)

The building-block of the most complex reasoning path is a single rule. All expert system tools process a single rule at a time.

Rules can be structured to perform backward or forward chaining or both along reasoning paths. In backward chaining, a rule can be used to verify a condition in another rule. In forward chaining, a rule can trigger the activation or the evaluation of other rules. Some expert system tools provide mechanisms for only forward or only backward chaining, others provide for both, and yet others provide for the use of the same rule in a forward or backward chaining mode. In the last case, rule evaluation is bi-directional, that is the system can either prove the hypothesis (goal-driven) or draw conclusions from the conditions (data-driven).

In the following, examples are provided of the type of backward, forward, and mixed chaining required for representing the reasoning path for landform interpretation.

It should be also stressed that besides the choice for forward and backward chaining, there is an issue of forward and backward reasoning. Forward reasoning implies starting from what it is known and trying to prove the unknown hypotheses. Backward reasoning implies starting from what needs to be proved and request the pertinent data to prove it. Backward reasoning can be implemented in a forward or backward chaining mode. Forward reasoning can be also implemented in a forward or backward chaining mode. Therefore, the mode of reasoning is not bounded by the mode of chaining available in the tool, however, it is greatly facilitated by the availability of both methods of rule execution.

Assuming that the value of a slot involved in one of the rule's conditions is known, by an action of a user volunteering (giving) the value of that property, the rule, as a chunk of knowledge, will become relevant and the system can use this rule to try to prove or disprove the hypothesis and make further inferences. This procedure of starting with data to evaluate rule conditions is called forward chaining.

If

topographic_form is "plain"
And drainage_pattern is "dichotomic"
And drainage_texture is "coarse"
And soil_tone is "light"
And land_cover is "barren","shrubs"
And vegetation is "shrubs"
And special is "fan shaped"

Then H_alluvial_fan is confirmed.

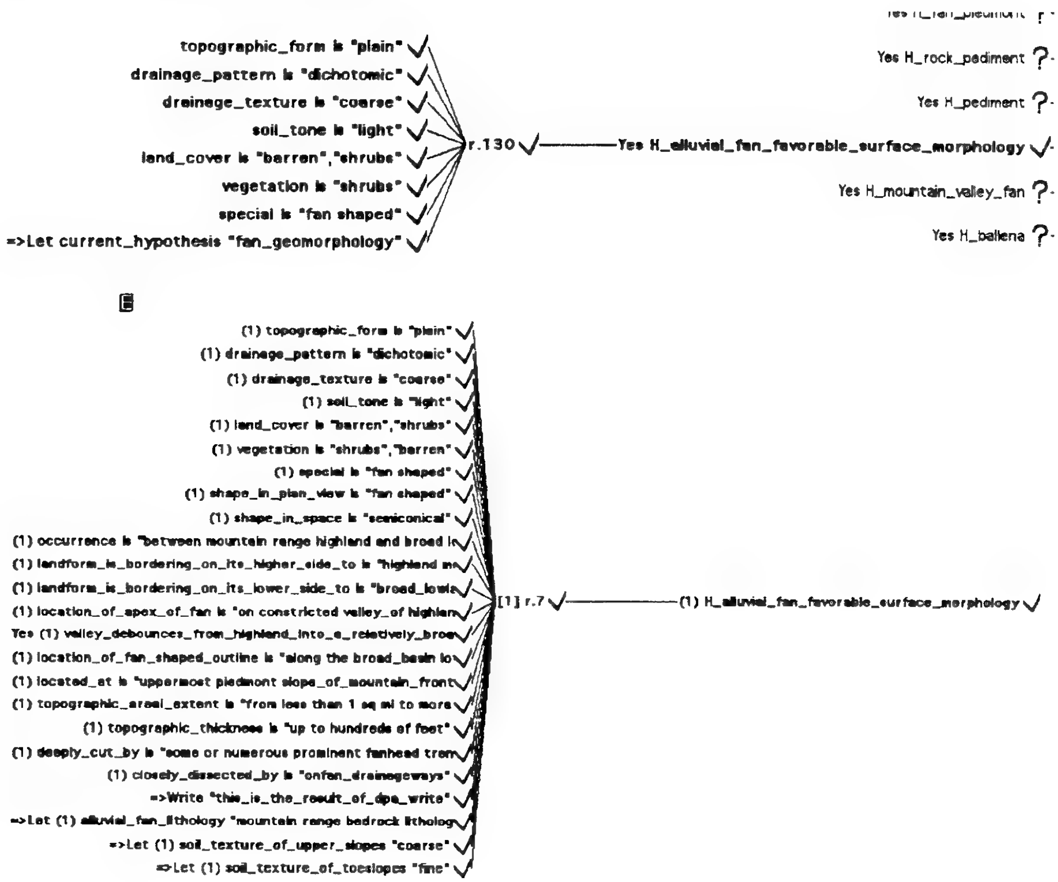


Figure 11. Evaluation by backward or forward mode of a single rule H_alluvial_fan_surface_morphology in different versions of the rule.

3.2.2 Multiple rule evaluation by backward chaining on an unevaluated hypothesis

Since a hypothesis has a value, it can appear in the LHS of a rule as a condition the system will verify. Figure 12 shows this situation where a rule whose hypothesis is "presence of rockfall" has an unevaluated condition which is itself another hypothesis "erosion_at_the_base_of_slope" that requires verification in order for the system to evaluate the "presence of rockfall" to "true." As a subtask in the evaluation of "presence of rockfall", the system will try to verify whether erosion_at_the_base_of_slope is true and must find one or more rules with erosion_at_the_base_of_slope as the hypothesis. At this point, the system needs to evaluate the conditions in the LHS of the rule leading to erosion_at_the_base_of_slope.

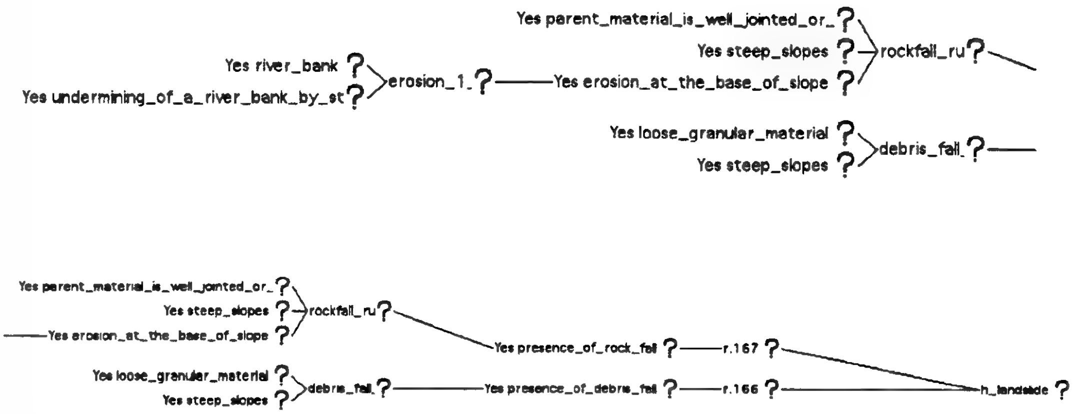


Figure 12. Hypothesis as a condition

3.2.3 Multiple rule evaluation by backward chaining through AND/OR tree

The structure shown in Figure 13 represents a typical AND/OR rule diagram wherein multiple rules share the same hypothesis. The first tier from the hypothesis is always an "or" decision while the second tier is an "and" decision. This arrangement of rules is expandable and may be used repeatedly at many levels of depth and can involve many rules as shown in Figure 14.

In the above cases, there might be conflicts between rules because more than one rule may lead to a single hypothesis. There are special mechanisms, called conflict resolution strategies in expert system tools to help us deal efficiently with such conflicts in a user-defined fashion.

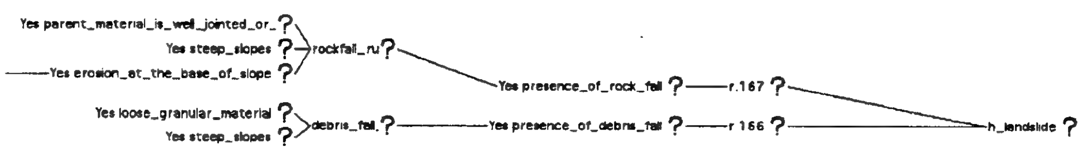


Figure 13. Typical AND/OR rule diagram generated by the hypothesis h_landslide

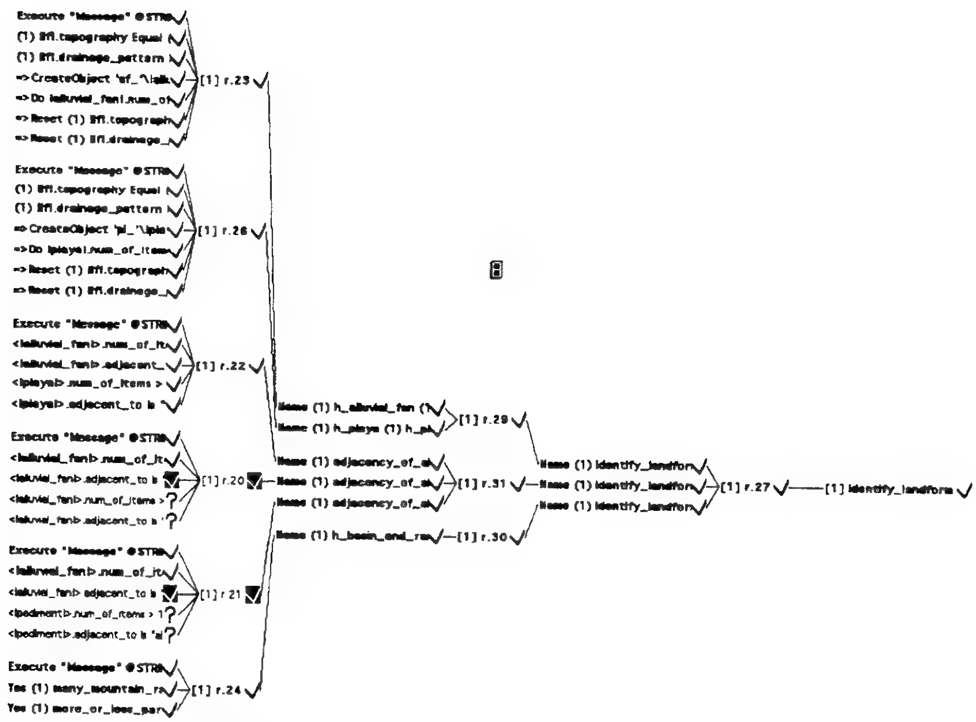


Figure 14. Backward chaining with multiple hypothesis

4. Additional types of rules and inference paths required for expanding the previous approaches

In the present conceptualization and formalization effort for a proper representation of the landform interpretation reasoning, it is postulated the use of the following types of rules.

4.1 Rules which pertain to the interpretation of landforms from their pattern elements.

These rules may be activated in a backward mode when the user wishes to suggest a possible landform hypothesis to be investigated or in a forward mode when the user, having no idea about the presence of a certain landform hypothesis, wishes to be prompted and to provide pattern element values of a site which may eventually lead to a landform hypothesis. For example, in Figure 9 the indicated rule "H_alluvial fan surface morphology" can be suggested for evaluation by this or similar rules, or the user may volunteer the value of any of the pattern elements appearing in the left part of the rule, an action which will activate the rest of the pattern elements for competing the rule evaluation in a forward manner.

4.2 Rules which pertain to the interpretation of landforms from their geomorphologic indicators

These rules may be activated in a backward mode when the user wishes to suggest a possible landform hypothesis to be investigated or in a forward mode when the user, having no idea about the presence of a certain landform geomorphic hypothesis, wishes to provide **geomorphic indicators** of a site which may eventually lead to a landform hypothesis (Figure 15).

IF		
Is	composed_of	"crudely_sorted_and_stratified_alluvium_with_or_without_d ebris_flow_deposits"
Yes	downslope_location	
Is	current_hypothesis	"fan_geomorphology"
THEN	true	H_alluvial_fan_favorable_geomorphic_process

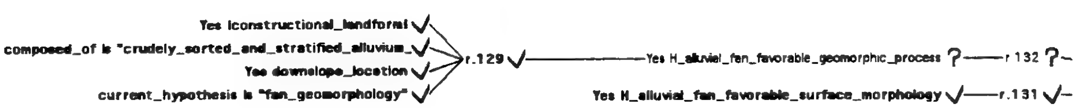


Figure 15. Simplified geomorphic origin rule (backward and forward)

4.3 Rules which pertain to the interpretation of landforms from their regional context.

The use of regional context may have various intentions. In this formalization of regional context, when any two landforms are found, the system checks their spatial proximity. The reason being that certain landforms are known to be adjacent to certain other landforms, e.g. floodplain to terrace, playa to valley fill, valley fill to alluvial fan, alluvial fan to alluvial fan (bahada), alluvial fan to pediment. Only when the regional context rules find two legitimate landforms next to each other, they prove the hypothesis of an adjacency of those landforms. Adjacencies not known to the system should not be permitted, implying that the system must prompt the user for this "inconsistency" so that he could check the situation and perhaps run the system again.

The following example (Figure 16) shows that rule 2, which is activated when the number of landforms

found to belong in the alluvial fan and the playa classes are each greater than one, examines if the interpreted alluvial fan object is next to a playa object and vice versa. The hypothesis "adjacency of alluvial fan to playa" is suggested by the user for backward evaluation in Figure 17. Upon that suggestion, the system is prompting the user to provide his interpretation about the proximity of the various landforms (Figure 18, Figure 19). Upon obtaining satisfactory answers about the proximity of the said landforms, the system is setting the unknown values of the "adjacent to" slot for both landform instances (af_1=alluvial fan and pl_1=playa) to their verified values "playa" and "alluvial fan" correspondingly (Figure 20).

In Figure 21 it is shown the rule "adjacency of alluvial fan to playa" being invoked by the context mechanism linked to the Basin and Range physiographic rule. This is but one reasoning scenario, there are alternative methods for invoking this regional context rule. The context mechanism is a weak link which connects the two knowledge islands.

Rule 2

If <lalluvial_fanl>.num_of_items is greater than 1
And <lalluvial_fanl>.adjacent_to is "playa"
And <lplayal>.num_of_items is greater than 1
And <lplayal>.adjacent_to is "alluvial fan"
Then **adjacency_of_alluvial_fan_to_playa**
is confirmed.

Figure 16. Simplified regional context rule concerning two landform types

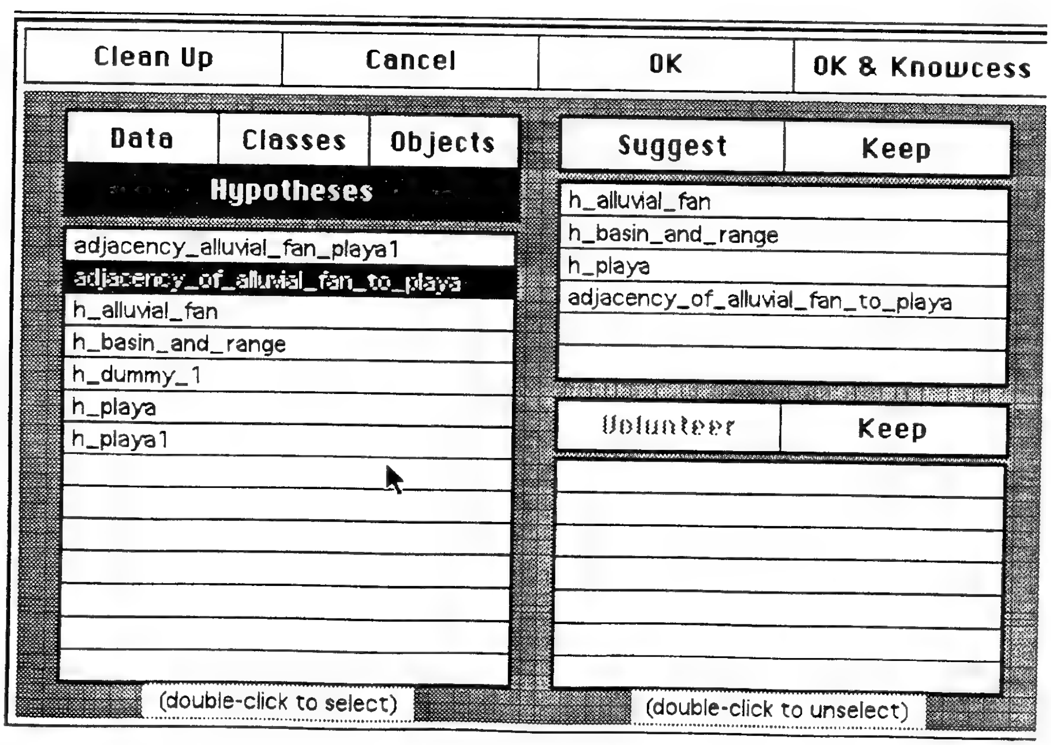


Figure 17. The user is suggesting certain hypothesis to investigate including the one for the check of adjacency between landforms

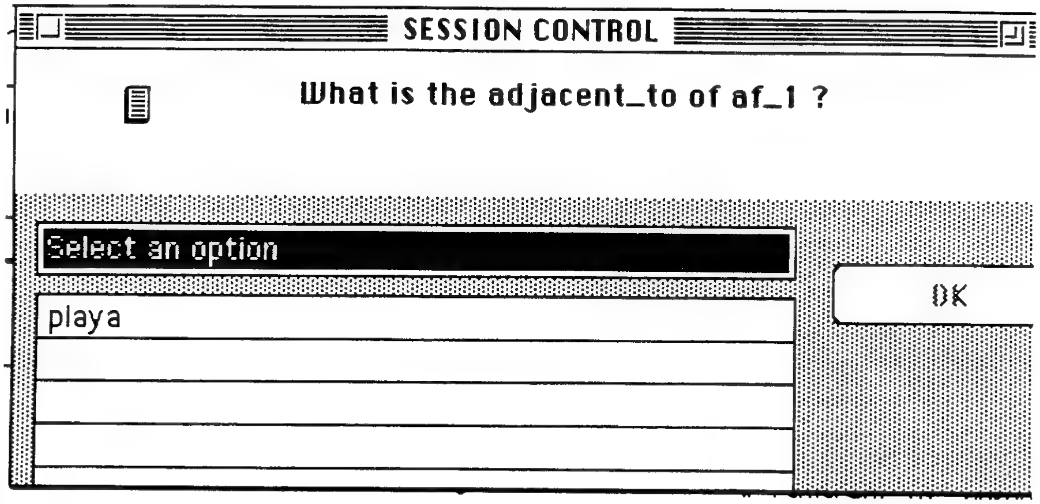


Figure 18. The user provides input as to which landform is next to another landform: playa is next to an alluvial fan

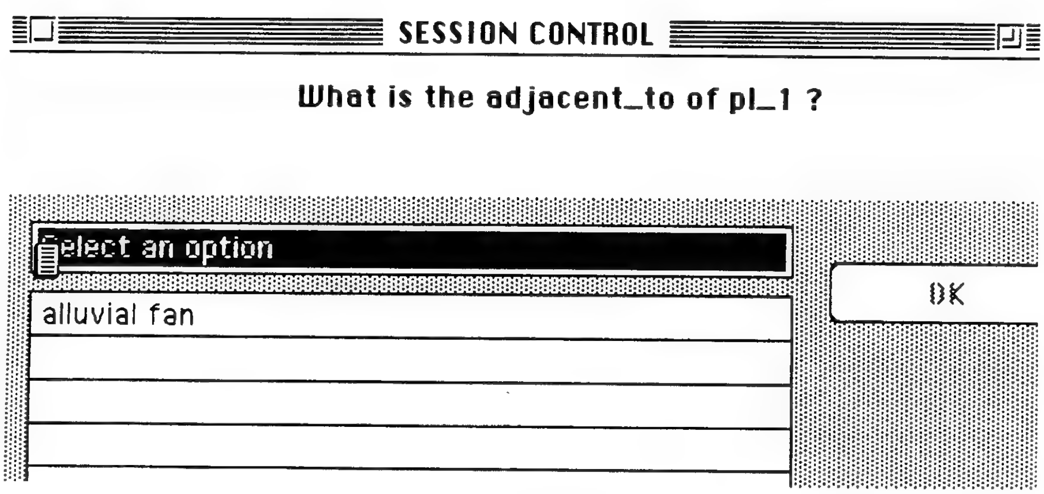


Figure 19. The user provides input as to which landform is next to another landform: alluvial fan is next to playa

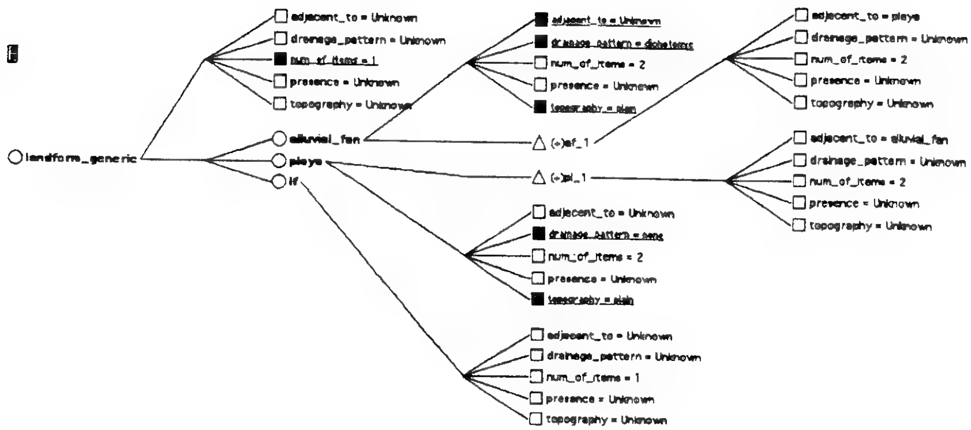


Figure 20. The adjacency rule has been proved and the slot adjacency_to of all interpreted landforms have taken the proper value

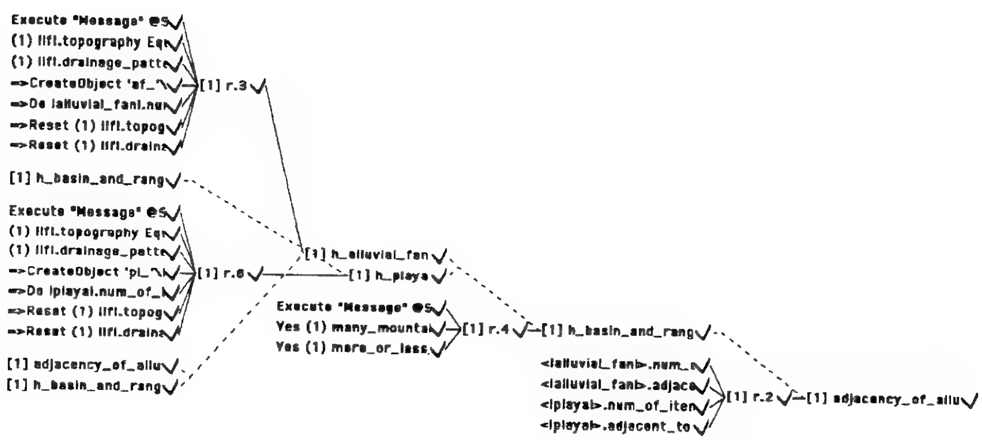


Figure 21. The rule of adjacency is connected here by a context (weak) link with the rules concerning pattern elements and physiographic analysis

4.4 Rules which pertain to the interpretation of physiographic regions (provinces, sections) from their indicators.

The use of physiographic context may have various intentions. In this formalization of physiographic context, the user is able to perform physiographic region analysis in two methods.

In the first, the user can suggest a physiographic region hypothesis and in this case the system will prompt him for the physiographic indicators so that to prove or to disprove the set hypothesis.

If the user has no prior knowledge so that to suggest the investigation of a specific physiographic region hypothesis, then the physiographic analysis rules will request the user for the needed physiographic indicators so that to search the knowledge base for a match with any of the available physiographic regions.

Figure 22 shows a simple rule for the hypothesis of Basin and Range with only two evidences. This rule may work in a backward or forward fashion.

In the second method, upon performing the physiographic analysis explained above, the system guides the user to interpret the physiographic parts of a physiographic region and subsequently the landforms that may be found there. For example in the case of the Basin and Range province, the user is guided to decide between (Figure 23, Figure 24, Figure 25)

- the piedmont landforms
- the basin floor landforms, and
- the mountains of the range landforms.

Upon the user selection of a piedmont landform, the user is guided for the landforms of the piedmont, e.g., alluvial fan, pediment, etc.

The above process may work in a forward fashion as well. That is, upon proving the hypothesis of an alluvial fan landform, the user is guided into the hypothesis of a piedmont, and subsequently to that of the Basin and Range physiographic province.

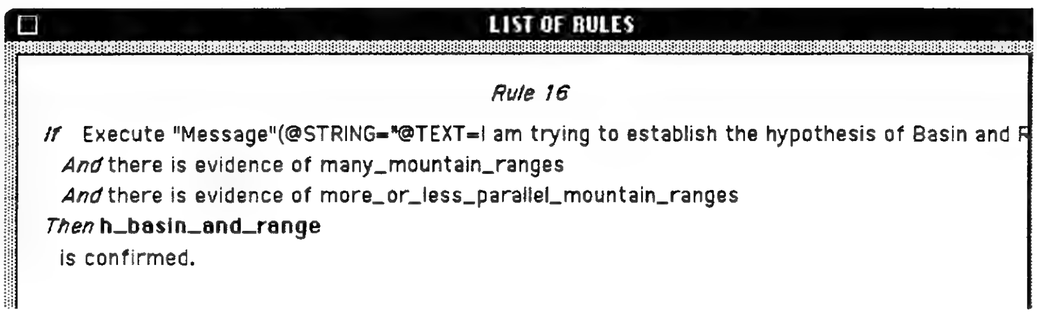


Figure 22: Simplified rule for physiographic region identification

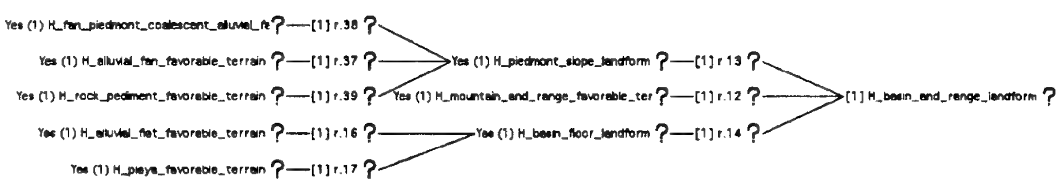


Figure 23. A partial reasoning path connecting the hypothesis of the Basin and Range province and the alluvial fan landform

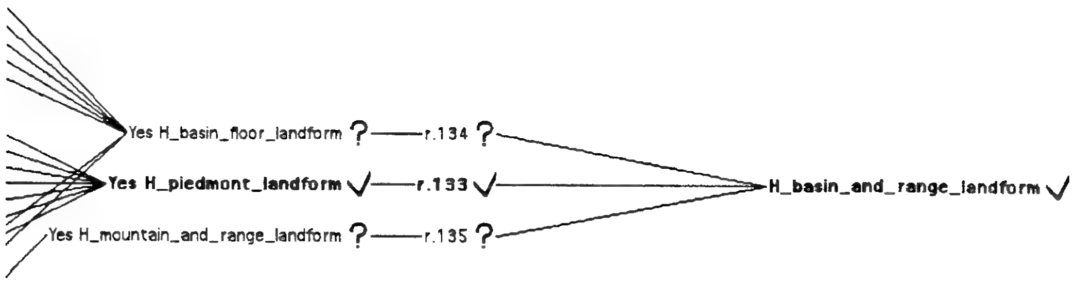


Figure 24. A partial reasoning path connecting the hypothesis of the Basin and Range province and the piedmont landforms

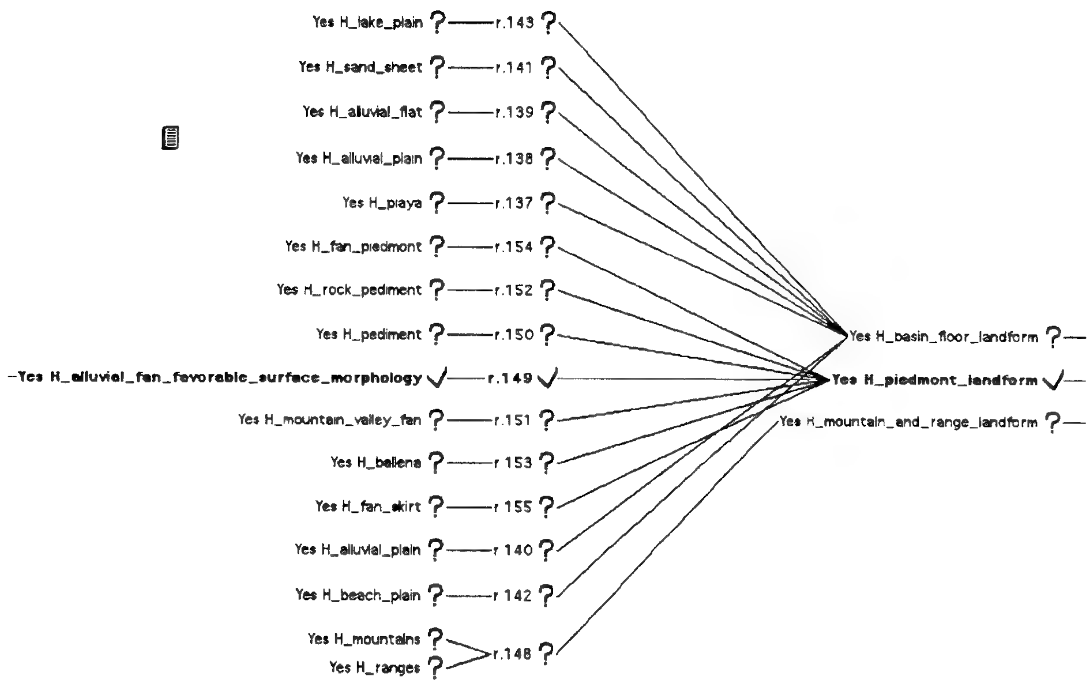


Figure 25. A partial reasoning path connecting the hypothesis of the basin_floor_landforms, piedmont_landfroms, and mountain_and_range landforms with a variety of landforms expected in the Basin and Range province

4.5 Rules which pertain to the interpretation of landforms from a combined evidence of pattern elements, geomorphic origin, regional context, and physiographic context.

While a landform hypothesis (e.g., alluvial fan) may be true because of the pattern element rule, it may not be true from the geomorphic, physiographic, or regional rules. The following type of rule (Figure 26) aims at grouping these partial evidences for a landform into a more integrated evidence.

Figure 27 shows how, in a backward or forward reasoning mode, the system is using two different rules for proving or disproving of the hypotheses:

- H_alluvial fan favorable surface morphology, and
- H_alluvial fan favorable regional environment

Subsequently, these are combined in the hypothesis "H_alluvial fan favorable terrain" (Figure 26).

If terrain is a member of |landform| And there is evidence of H_alluvial_fan_favorable_climate And there is evidence of H_alluvial_fan_favorable_physiographic_section And there is evidence of H_alluvial_fan_favorable_pattern_elements And there is evidence of H_alluvial_fan_favorable_surface_morphology And there is evidence of H_alluvial_fan_favorable_site And there is evidence of H_alluvial_fan_favorable_association And there is evidence of H_alluvial_fan_favorable_geomorphic_process And there is evidence of H_alluvial_fan_favorable_regional_environment Then H_alluvial_fan_favorable_terrain is confirmed.

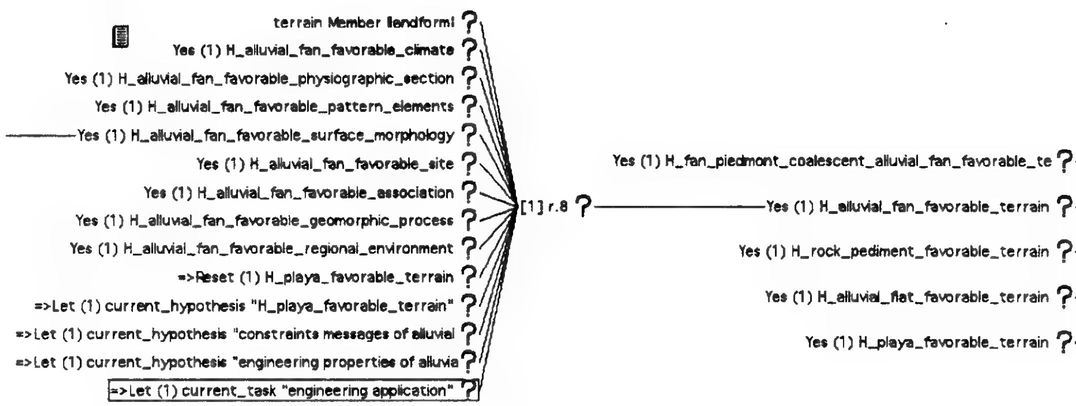


Figure 26. An evidence combining rule for the alluvial fan favorable terrain

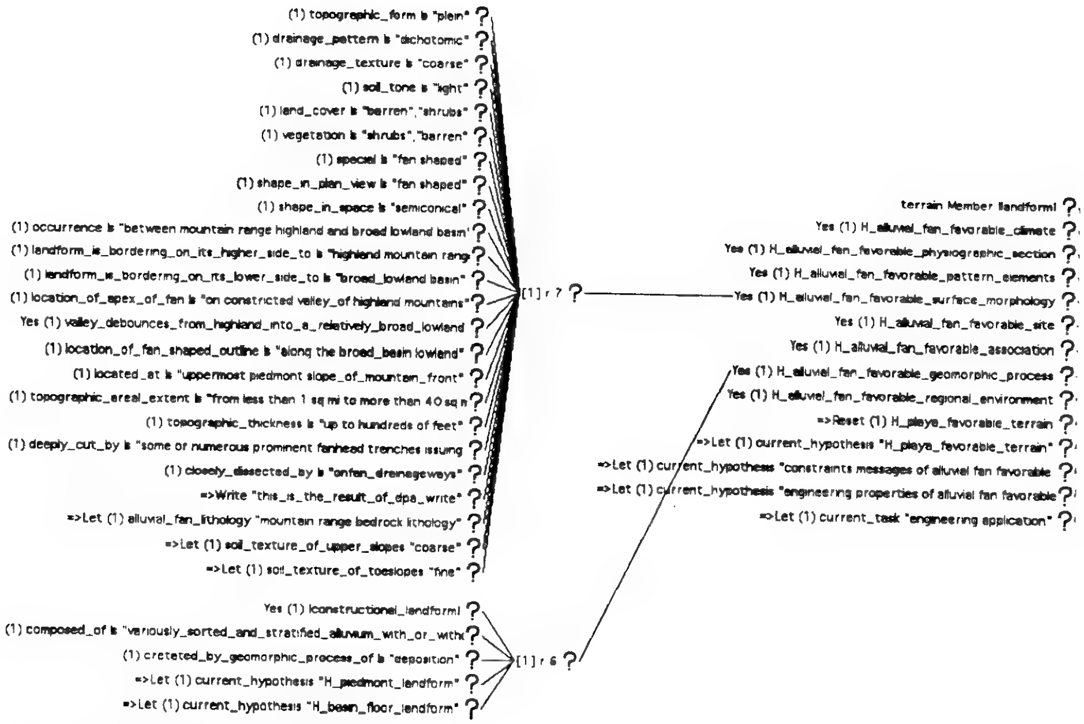


Figure 27. The alluvial fan landform is being inferred from surface morphology (pattern elements) and geomorphic indicators

5. Additional examples of rules and reasoning paths

5.1 Example 1

These rules (Figure 28), reflecting landform identification by pattern elements, adjacency rules, and physiographic context are reasoning backward by suggesting each hypothesis, or forward by volunteering the current task -being pattern element, geomorphic origin, or physiographic context.

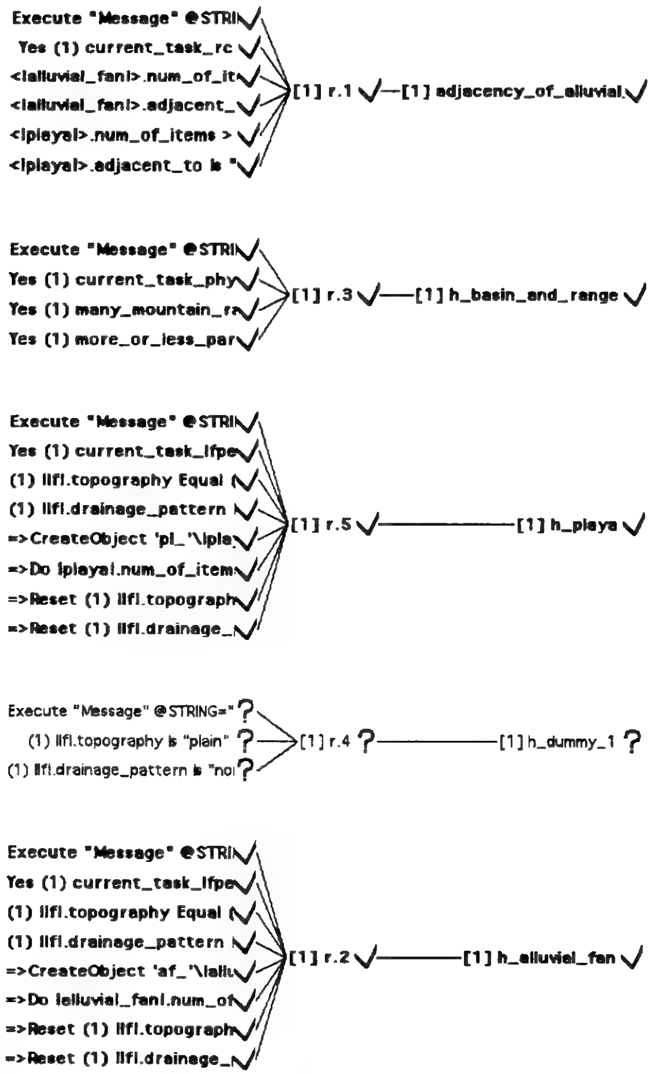


Figure 28. Rules reflecting landform identification by pattern elements, adjacency rules, and physiographic context (backward or forward)

5.2 Example 2

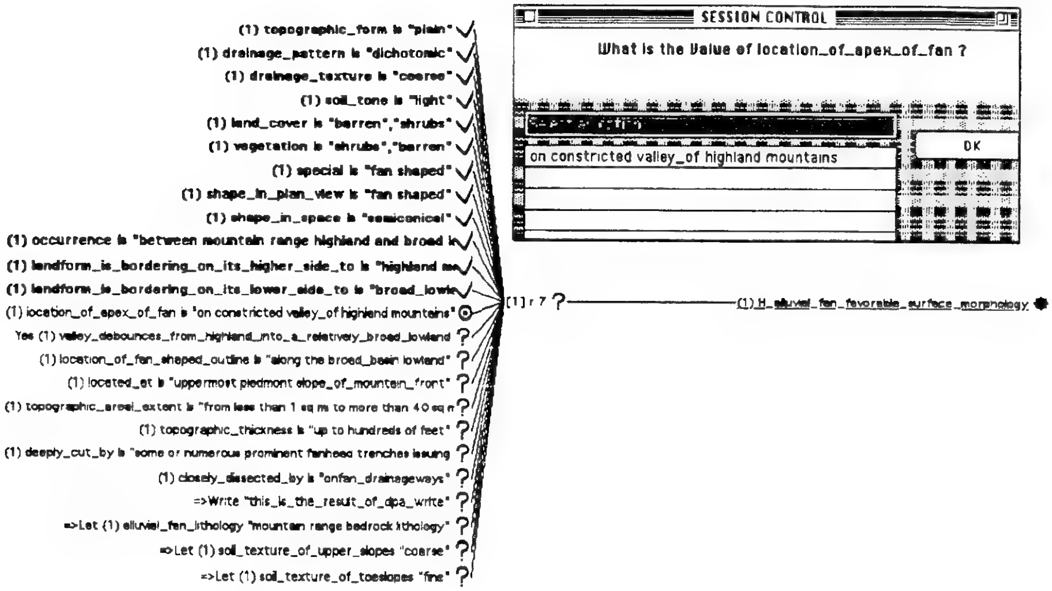


Figure 29. The user is answering the queries of the system, providing each pattern element value

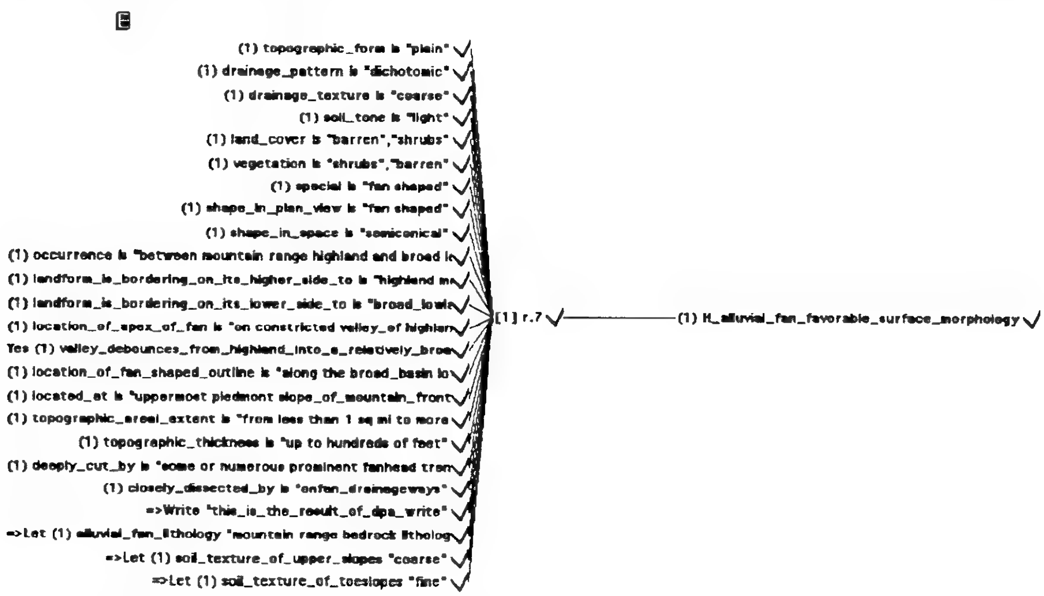


Figure 30. The user has answered all queries of the system regarding pattern elements correctly and the hypothesis of an alluvial fan from surface morphology has been established as true

5.3 Example 3

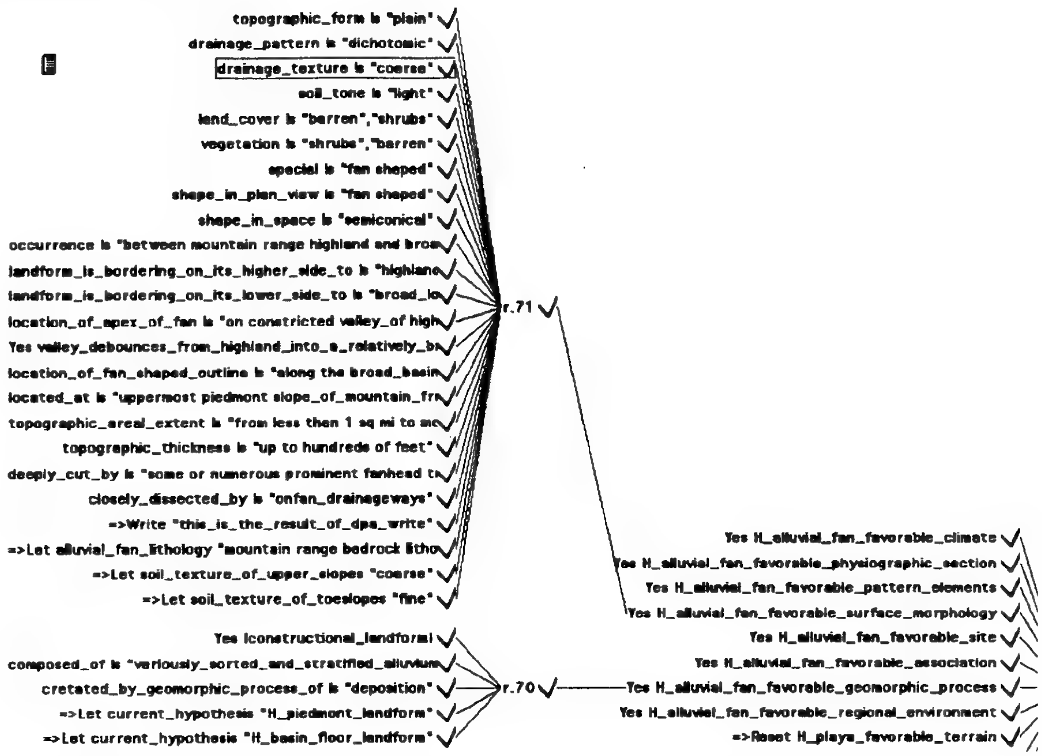


Figure 31. The user has answered all queries of the system regarding pattern elements and geomorphic context correctly and the hypothesis of an alluvial fan from surface morphology as well as the hypothesis of an alluvial fan favorable terrain from geomorphic processes have been established as true

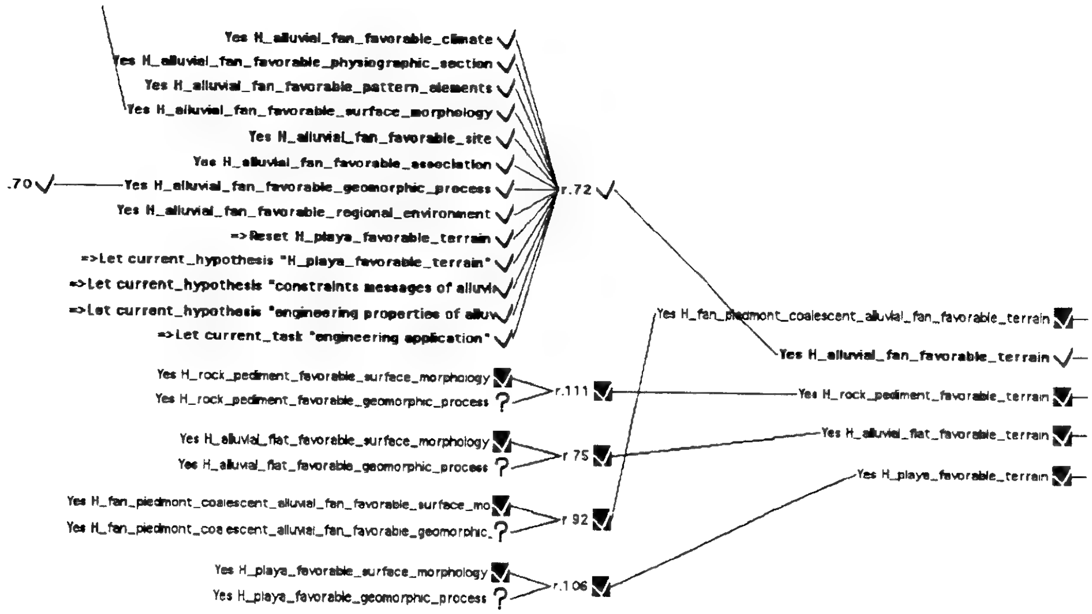


Figure 32. The user has answered the queries of the system regarding all aspects of reasoning for alluvial fan favorable terrain and therefore the combined evidence rule has been established as true, while the rest of the hypotheses concerning the other landforms (pediment, playa, etc.) have failed

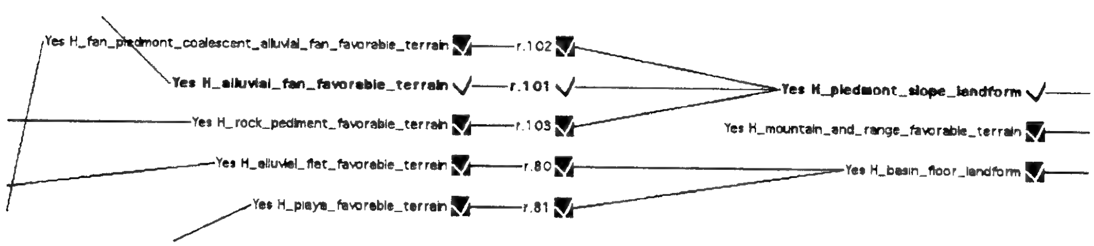


Figure 33. The established hypothesis of an alluvial fan favorable terrain proves true the hypothesis of a piedmont slope landform

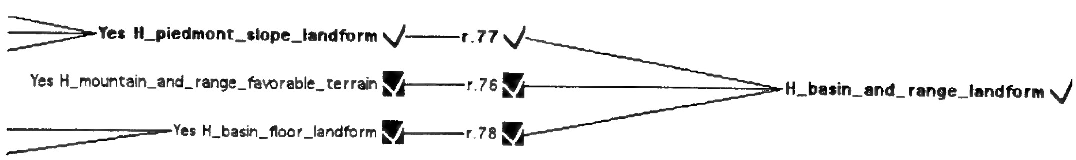


Figure 34. The established hypothesis of piedmont slope landform proves true the hypothesis of a Basin and Range landform

5.4 Example 4

In this example the system starts by the user giving the top goal "acquire from user the number of landforms of the site" (Figure 35). This goal, upon getting from the user the required number for landforms (Figure 35), asks for the pattern elements of each landform as it is showing in the following examples (Figure 36, Figure 35, Figure 37). Upon getting the pattern elements of each landform (Figure 36, Figure 35), it creates unknown landform instances lf_i (Figure 38), tests the landforms as to their type (Figure 35), performs regional and physiographic analysis, and at the end it creates the identified instances (objects) of each identified object Figure 38.

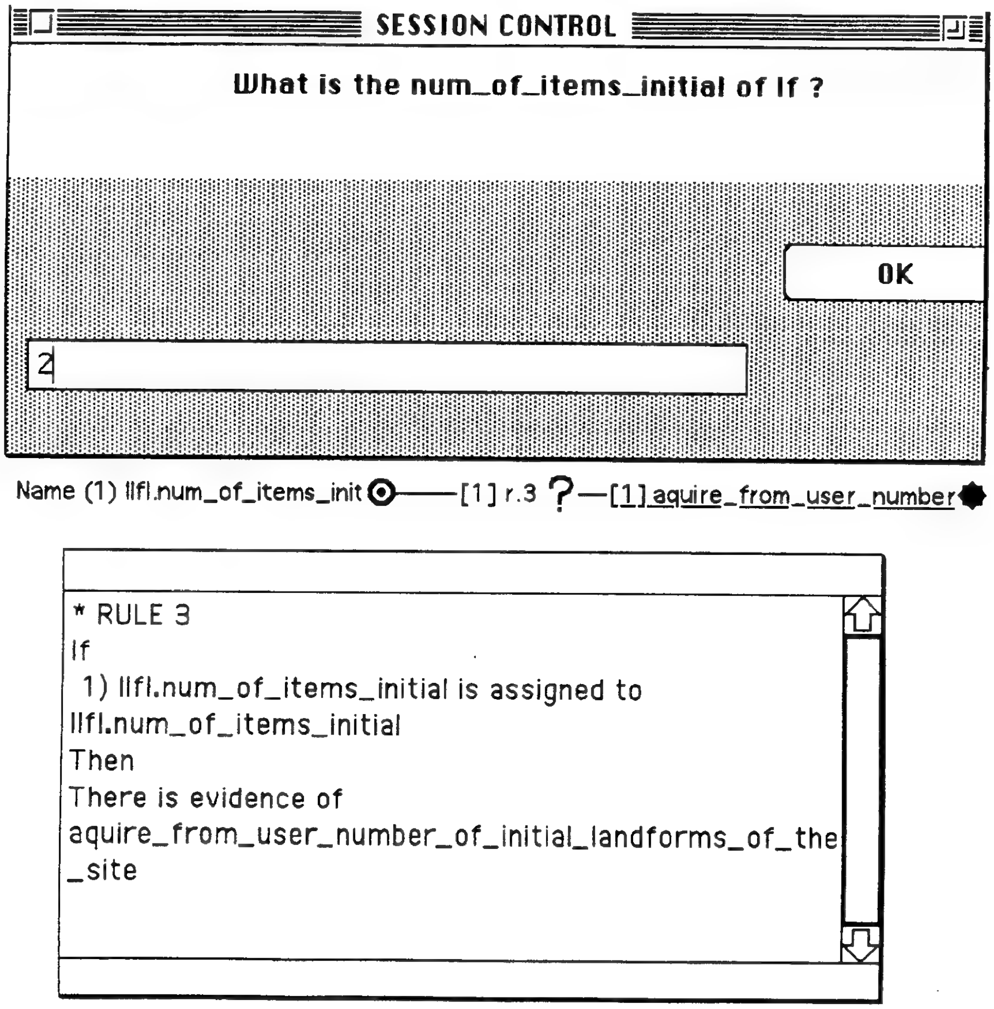


Figure 35. The user is giving the top goal "acquire from user the number of landforms of the site" which requests the number of landforms to examine. The user responds for two landforms.

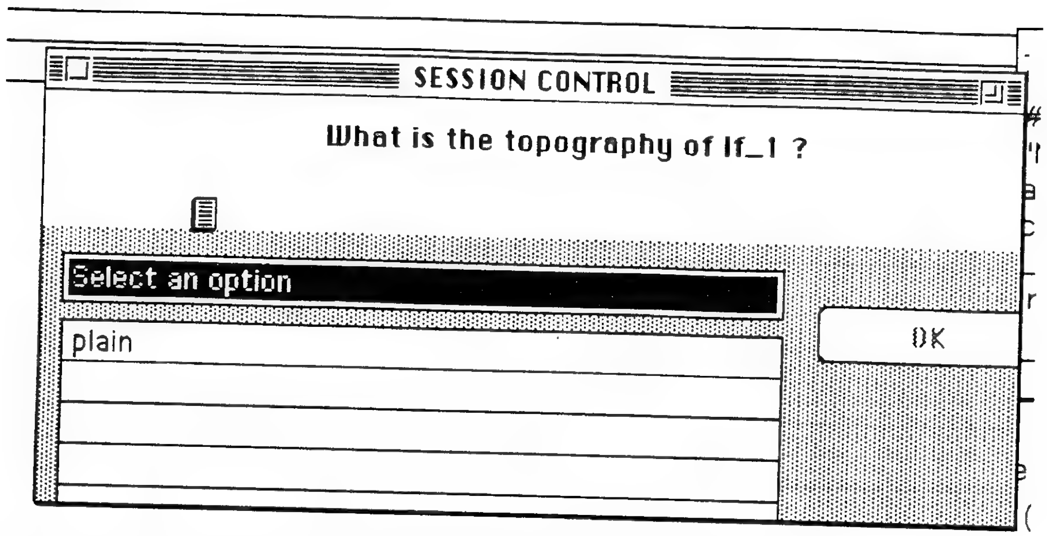


Figure 36. The system gets from the user the values of the pattern elements

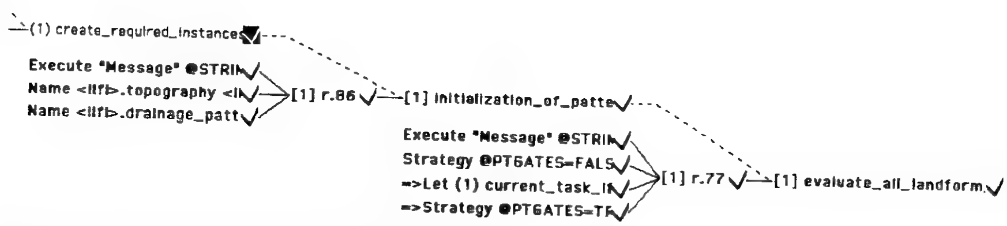


Figure 37. The system proceeds with contexts through the various tasks

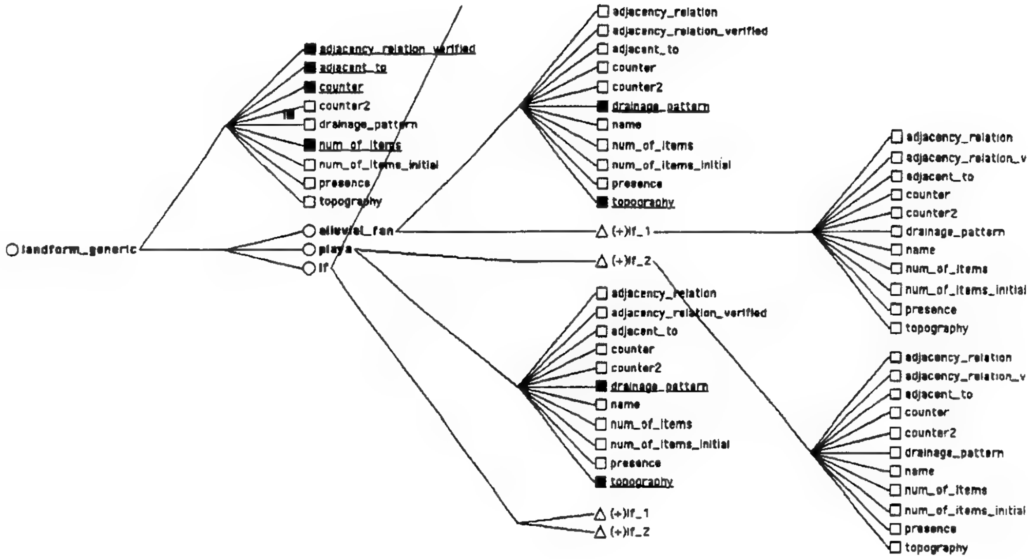


Figure 38. The system has created the initial instances of the two landforms and then upon infering their type, it copies them under the proper landform classes as their instances.

6. Knowledge Acquisition and Compilation

As it was explained during the identification and formalization stages of the landform-related knowledge, it was necessary to expand the landform-pattern element approach to include an expanded range of landform indicators such as additional pattern elements, indicators of regional context, indicators of physiographic context, and indicators of geomorphic process context.

This knowledge was compiled and, systematized to a certain degree, with great difficulty because of the variety of opinions in the textbooks regarding the landform indicators and their values and also because the systematic organization had to be made in an adhoc trial-and-error manner.

The results of this collected and systematized factual (qualitative and declarative) knowledge is presented in the tables of this section. It is organized into classes (Pattern Elements, Geomorphology, Geomorphometry e.t.c.). Each class is characterized by attributes (slots) and attribute values.

The following landforms and physiographic regions are described in Tables 8-15:

- Alluvial Fans
- Valley Fills
- Playas
- Continental Alluvium
- Physiographic Context
- Sonoran Desert
- Great Basin

TABLE 8 ALLUVIAL FANS		
EVIDENCE CLASS	**Slot**	**Value**
Pattern Elements		
	Drainage Pattern	dichotomic, radial-braided
	Gullies	no, few
	Tone	light gray
	Topography	fan-shaped
	Vegetation	natural cover scattered scrub, grass
	Distinguished from	from Deltas by its perspective slope toward apex
Geomorphology		
	Landform Type	depositional alluvial deposit fluvial landform
	Climate	arid semi-arid
	Process	fluvial
	Agent	loaded stream
	Water Regime	ephemeral intermittent
	Stream Process	braided
	Drainage Texture (density)	
	Depositional Mechanism	abrupt change of stream gradient & velocity
	Depositional Area	on adjacent plane in front of a valley mouth
Geomorphometry		
	Planimetric Shape	fan shaped outline
	3d Shape (geometric shape)	conical a cone radiating downslope
	Shape Boundary	distinct
	Concavity/Convexity	concave radially convex transversely
	Highest Portion	apex
	Lowest Portion	outer fringe
	Surface Height	low
	Size (radial extent)	few hundred meters to tens of kilometers
	Surface Slope	1 to 10 degrees gently sloping
	Profile Development/gullies	little
	Surface Verbal Description	a fan rises gently towards its apex at 1-10 degrees, the fan slopes gently towards its outer fringe
Material		
	Rock	
	Origin of Material	sediment from loaded stream
	Kind of Material	bed load (larger particles rolled along stream bed) suspended load (smaller particles picked up and carried forward in suspension)
	Sediment Composition	sand and gravel, also a small portion of silt & clay (more in humid climate)
	Spatial Distribution	• coarsest material near apex • finer material near the margin of the fan • apex contains boulders & cobbles
Regional context		
	adjacent to	flat plain

TABLE 8 ALLUVIAL FANS		
EVIDENCE CLASS	Slot	Value
		valley mouth
	higher than	plane
	lower than	valley mouth
	contained in	adjacent plane
Physiogr. Context		
	contained in	Mountain Range Province
	contained in	Sonoran Desert Section
	contained in	Great Basin Section
	contained in	piedmont of a piedmont
	out of	pediment
	lower than	
	lower than	piedmont junction

TABLE 9 VALLEY FILLS		
EVIDENCE CLASS	**Slot**	**Value**
Pattern Elements		
	Drainage Pattern	Parallel, braided
	Gullies	none
	Tone	uniform light gray
	Topography	filled valley bottoms
	Vegetation	natural cover cultivated
Geomorphology		
	Landform Type	depositional alluvial deposit fluvial landform
	Climate	arid semi-arid
	Process	fluvial
	Agent	loaded streams
	Water Regime	ephemeral intermittent
	Stream Process	braided
	Drainage Texture	
	Depositional Mechanism	loaded streams shift channel and deposit vast amounts of alluvial deposits during severe storms
	Depositional Area	flat valley bottom
Geomorphometry		
	Planimetric Shape	plane
	3d Shape (geometric shape)	gradually gently sloping plane
	Shape Boundary	
	Concavity/Convexity	plane
	Highest Portion	near the highlands
	Lowest Portion	near the valley bottom
	Surface Height	low
	Size	
	Surface Slope	gently sloping away from the highlands
	Profile Development/gullies	little
	Surface Pattern	rock islands
	Surface Verbal Description	flat valley bottoms gradually sloping from the highlands, interrupted occasionally by rock islands
Material		
	Rock	
	Origin of Material	alluvial sediments from highlands
	Kind of Material	alluvial sediments
	Sediment Composition	sand and gravel, also a small portion of silt & clay (more in humid climate)
	Spatial Distribution	coarsest material near the highlands finer material near the valley bottom
Regional context		
	lower than	highlands alluvial fans bahadas
	contains	playas
	adjacent to	alluvial fans bahadas
Physiogr. Context		
	contained in	Mountain Range Province
	contained in	Sonoran Desert

TABLE VALLEY FILLS		
EVIDENCE CLASS	Slot	Value
	contained in	Great Basin
	contained in	
	out of	pediment
	lower than	pediment
	lower than	piedmont junction

TABLE 11 PLAYA		
EVIDENCE CLASS	Slot	Value
Pattern Elements		
	Drainage Pattern	none
	Gullies	none
	Tone	light, scrabbled
	Topography	flat basin
	Vegetation	barren cultivated
Geomorphology		
	Landform Type	depositional fluvial landform dry lake bed
	Climate	arid semi-arid
	Process	fluvial
	Agent	shallow temporary lake
	Water Regime	ephemeral intermittent occasionally covered with shallow sheets of water
	Stream Process	
	Drainage Texture	none
	Depositional Mechanism	interior drainage & closed basin
	Depositional Area	base level plains of topographically closed drainage basins
Geomorphometry		
	Planimetric Shape	flat plane
	3d Shape (geometric shape)	plane horizontal
	Shape Boundary	
	Concavity/Convexity	plane
	Highest Portion	plane
	Lowest Portion	plane
	Surface Height	base level basin
	Size	few sq. m to 9.000 sq. km
	Surface Slope	horizontal in slope
	Profile Development/gullies	none
	Surface Pattern	temporary shallow lake, usually light photo tones
	Surface Verbal Description	lakebeds of baselevel plains of desert closed basins with internal drainage occasionally covered with shallow sheets of water, with little or no vegetation
Material		
	Rock	
	Origin of Material	alluvial sediments
	Kind of Material	
	Sedimentary Composition	stratified silt & clays with large soluble salt quantities
	Spatial Distribution	
Regional context		
	adjacent to	
	contained in	closed basins
	contained in	
Physiogr. Context		
	contained in	Mountain Range Province
	contained in	Sonoran Desert

TABLE 11 PLAYA		
EVIDENCE CLASS	Slot	Value
	contained in	Great Basin
	contained in	valley fills
	contained in	continental alluvium
	contained in	intermont basins
	out of	
	lower than	pediment
	lower than	alluvial fans
	lower than	bahadas
	lower than	piedmont junction

TABLE 12 Continental Alluvium		
EVIDENCE CLASS	**Slot**	**Value**
Pattern Elements	Slot	Value
	Drainage Pattern	internal, dendritic
	Gullies	few U-shaped
	Tone	uniform light gray
	Topography	broad flat plains
	Vegetation	natural cover cultivated
Geomorphology		
	Landform Type	depositional alluvial landform fluvial landform
	Climate	arid semi-arid
	Process	fluvial
	Agent	loaded streams
	Water Regime	ephemeral intermittent
	Stream Process	braided
	Drainage Texture	coarse (regional) drainage
	Depositional Mechanism	loaded streams, originated in mountains, deposit vast amounts of alluvial deposits on adjacent planes during severe storms
	Depositional Area	flat planes (adjacent to mountains)
Geomorphometry		
	Planimetric Shape	broad flat plane
	3d Shape (geometric shape)	flat plane
	Shape Boundary	
	Concavity/Convexity	plane
	Highest Portion	
	Lowest Portion	
	Surface Height	low
	Size	• very broad planes in regional scale • cover thousands of square miles
	Surface Slope	flat
	Profile Development/gullies	few U-shaped, badland erosion features along its edges
	Surface Pattern	buffalo wallows
	Surface Verbal Description	flat plains covering vast regions, occasionally broken by small circular flat bottomed depressions caused by wind erosion
Material		
	Rock	sedimentary
	Origin of Material	alluvial sediments from highlands
	Kind of Material	alluvial sediments
	Sedimentary Composition	sand and gravel also a small portion of silt & clay (more in humid climate)
	Spatial Distribution	coarser particles settle near the basin margin finer material is deposited near the basin center
Regional context		
	adjacent to	alluvial fans bahadas
	lower than	highlands

TABLE 12 Continental Alluvium		
EVIDENCE CLASS	Slot	Value
		alluvial fans bahadas
	contains	playas
Physiogr. Context		
	contained in	Mountain Range Province
	contained in	Sonoran Desert
	contained in	Great Basin
	contained in	
	out of	pediment
	lower than	pediment
	lower than	piedmont junction

TABLE 13 Evidence of the Basin and Range Province (Physiographic Context)		
EVIDENCE CLASS	**Slot**	**Value**
Province		
	province description	mountain ranges separated by desert basins
	province size	great (1/10 of the USA)
Ranges		
	geometry	ranges are roughly parallel
		a general straightness is more worthy than the opposite
	appearance	one or more (parallel) ranges
		ranges are smaller and larger
		the bulk of a range is fairly continuous
		within a range no great and sudden variation in height
		ranges are not deeply notched & segmented
	length	50-75 miles commonly
	width	6-15 miles are common
Mountains		
	(tectonic) process	tilted faulted, folded & eroded blocks,
	planimetric shape	plainly unsymmetrical (tilted faults blocks)
	mountain border	the course of mountain front marks usually a great fault
Valleys		
	shape	V-like
	frequency	mature dissection by angular valleys
	slopes	frequent occurrence of ravined slopes
		the meeting of valley floor & mountain side is abrupt
Basins		
	shape	basin are almost level
	shape	concave basins filled with sediments
Drainage		
	pattern	centripetal (internal)
	ending	leads to enclosed basins playas

TABLE 14 **Identification of Sub-Physiographic Units**			
		Sonoran Desert	**Great Basin**
EVIDENCE CLASS	**slot**	**value**	**value**
Geomorphometry			
	general description	mountain ranges intervening desert planes	mountain ranges intervening desert planes
	relative height	much lower in altitude	much higher in altitude
	range size	mountain ranges are smaller	mountain ranges are larger (lengths of 50-75 & widths of 6-15 miles are common)
Hypsometry			
	3000 ft contour indicator	an insignificant portion lies above 3000 ft	a significant portion lies above 3000 ft
	usual heights	more than 1/2 of surface is below 2000 ft	ranges most frequent altitudes are 7000-10.000 ft above sea level
	ranges %	1/5 is covered by mountain ranges	1/2 of the area is covered by mount ranges
	pediments %	2/5 of the area is covered by pediments	pediments are less prevalent
	basins %	2/5 of the area is covered by basins	1/2 of the area is covered by basins
Erosion cycle			
	overall degree of erosion cycle	the erosion cycle has proceeded further here	erosion cycle has proceeded less here
	relative age of ranges	mountain ranges are perhaps older	ranges are in a younger erosion stage
	relative degree mountain erosion cycle	greatly eroded mountain forms of a long erosion cycle	eroded mountains possibly at the first erosion cycle
Drainage			
	degree of unification/independence	union of basins in a common drainage system	independence of drainage basin
	drainage integration	drainage is more integrated (mainly in pediments)	drainage is either not or less integrated
	centripetal drainage	much of area has no centripetal drainage	interior drainage (centripetal) is highly characteristic
Tectonism			
	tectonic planimetric shape of mounts outline	most of the ranges are without the straight base lines relied on fault origin	the meeting of the valley floor and mountain range is abrupt and straight base lines are evident (faulting)
	tectonic interpretation	a minority of mountain ranges was interpreted as fault blocks	majority of ranges are eroded tilted fault blocks (plainly unsymetrical in slope)
Basins			
	evidence of pediments	pediments are much more prevalent	pediments are less prevalent
	evidence of concave basins	large areas are without concave basins of internal drainage	concave basins of internal drainage

7. References

Argialas, D., 1995. Towards Structured Knowledge Models for Landform Representation. Zeitschrift für Geomorphologie_(Accepted, in print)

Argialas, D., 1991. Implementing a Visual Vocabulary for Landform Analysis. Technical Report

Argialas, D., 1991. Developing a Visual Vocabulary for Landform Analysis. Technical Report

Argialas, D. & Narasimhan, R. (1988b): A production system model for terrain analysis knowledge representation. - Microcomputers in Civil Engineering, Elsevier Science Pub. Co., **3,** I: 55-73.

Argialas, D. & R. Narasimhan (I988a): TAX: A prototype expert system for terrain analysis. - Journal of Aerospace Engineering, American Society of Civil Engineers, **I**, 3: 151-170.

Argialas, D. (1989): A frame-based approach to modeling terrain analysis knowledge. - Technical Paper, Annual Convention of American Society for Photogrammetry and Remote Sensing, **3:** 311-319, April 2-7, 1989, Baltimore, Maryland.

Argialas, D., & C. Harlow (1990): Computational image interpretation models: an overview and a perspective. - Photogrammetric Engineering and Remote Sensing, **56**, 6: 871-886.

Argialas, D., & O. Mintzer (1992): The potential of hypermedia to photointerpretation education and training. - In: L. Fritz and J. Lucas (eds.): International Archives of Photogrammetry and Remote Sensing, XVII ISPRS Congress, Washington DC. August 2-14, 1992, Commission VI, XXIX, part B: 375-381

Argialas, D., Lyon, J. & Mintzer, O. (1988): Quantitative description and classification of eight drainage pattern types. - Photogrammetric Engineering and Remote Sensing, American Society of Photogrammetry and Remote Sensing, 54, 4: 505-509.

Avery, Eugene. 1968. Second Edition. Interpretation of Aerial Photographs.

Bandat, H., 1962. Aerogeology, Gulf Publishing Company, Houston, Texas.

Belcher, D. (I948). "The engineering significance of landforms," Highway Research Board Bulletin, No. I3, pp. I25.

Chandrasekaran, B., 1982. Decomposition of domain knowledge into knowledge sources: The MDX approach. Proceedings of the Fourth National Conference of Canadian Society for Computational Studies of Artificial Intelligence.

Chikishev, A., ed., 1973. Landscape Indicators, Plenum Press, New York.

Drury, S., 1987. Image Interpretation in Geology, Allen & Unwin, Boston.

Fenneman, N. 1931. Physiography of the western United States, McGraw-Hill Book Co., New York, NY.

Fenneman, N., 1938. Pysiography of the eastern United States, McGraw-Hill Book Co., New York, NY.

Fikes, R., and T. Kehler, (1985). "The role of frame-based representation in reasoning," Communications of the ACM, September 1985, Vol 28, Number 9, pp. 904-920.

Hall, C., and Benz, S. (I985). "A knowledge-based photointerpretation system." National Defense, Vol. LXIX, No. 404, pp. 54-62.

Hammond H., 1954. Small-Scale Continental Landform Maps: Annals Of Assoc. Of American Geographers.. V44, P. 33-42

Hammond H., 1958. Procedures In The Descriptive Analysis Of Terrain.. Final Report On Project R-387-015: Dept. Of Geography, University Of Wisconsin, Madison, WI.

Hammond H., 1964a. Analysis Of Properties In Landform Geography: An Application To Broadscale Land Form Mapping.. Annals Of Assoc. Of American Geographers V. 54, P. 11-19

Harmon, P. & King, D. (I985): Expert systems: artificial intelligence in business. - Wiley & Sons, New York.

Hayes-Roth, F., Waterman, D. & Lenat, D. (I983): Building expert systems. - Addison-Wesley, Reading, MA.

Hoffman, R. & R. Pike (I993): On the specification of the information available for the perception and description of the natural terrain. - In: J. Flash & P. Hancock (eds.): The ecology of human-machine interaction (volume 2). L. Erlbaum Assoc., Hillsdale, NJ.

Hoffman, R. (I985): What's a hill? An analysis of the meaning of generic topographic terms. - Final Report, Control No. DAAG-29-D-0100 Scientific Services Program, U.S Army Research Office, Alexandria, VA.

Hoffman, R. (I987): The problem of extracting the knowledge of experts from the perspective of experimental psychology. - The AI Magazine, **8**, (2): 53-67.

HyperCard Stack Design Guidelines (1989): Apple Computer, Inc. - Addison Wesley Publishing Company, Reading, Massachusetts.

Intellicorp 1989. KEE software development system, User's manual. Intellicorp Inc., Mountain View, CA.

IntelligenceWare (1986): Intelligence/Compiler User's Manual. - Los Angeles.

Jackson, P. (I986): Introduction to expert systems. - Addison-Wesley, Reading, MA.

Leighty, R. (I979). "Research for information extraction from aerial imagery." in: Remote Sensing Symposium, U.S. Army Corps of Engineers, Engineer Topographic Laboratory, Reston, VA.

Leighty, R., 1973. A Logical Approach Toward Terrain Pattern Recognition for Engineering Purposes, Ph.D. Dissertation, Department of Civil Engineering, Ohio State University, Columbus, Ohio, 231 pp.

Leuder, D.R. 1959. Aerial photographic interpretation. New York: McGraw-Hill.

Lillelsand, T., & R. Kiefer (1979): Remote sensing and image processing. - John Wiley and Sons, New York.

Lobeck, A. (I932). Atlas of american geology. The Geographical Press, Columbia University, New York, NY.

Lueder, D., 1968. Aerial Photographic Interpretation: Principles and Application, McGraw-Hill, New York.

Mark, J. (I976). "Computer analysis of photo pattern elements." Photogrammetric Engineering and Remote Sensing, Vol. 42, No. 4, pp. 545-556.

Miller, V.C. and C.F. Miller 1961. Photogeology. New York: McGraw-Hill.

Minsky, M., (1975): A framework for representing knowledge. - In: Winston, P. (ed.): The psychology of computer vision: 211-277; McGraw-Hill, New York, NY.

Mintzer, O. & J. Messmore (1984): Terrain analysis procedural guide for surface configuration. - Technical Report ETL-0352, U.S. Army Corps of Engineer, Engineer Topographic Laboratory, Fort Belvoir, Virginia.

Mintzer, O. (1983): Engineering applications. - In: Colwell R. (ed.): Manual of Remote Sensing. American Society of Photogrammetry. - Falls Church, Virginia.

Mintzer, O., 1988. Research in terrain knowledge representation for image interpretation and terrain analysis. U.S. Army Symposuim on Artificial Intelligence Research for Exploitation of Battlefield Environment, Nov. 1-16, 1988, El Paso, TX, pp. 277-293.

Mollard, Jack. 1974. Landforms and Surface Materials of Canada: A Stereoscopic Airphoto Atlas and Glossary.

Narasimhan, R. & Argialas, D. (1989): Computational approaches for handling uncertainties in terrain analysis. - Technical Paper, Annual Convention of American Society for Photogrammetry and Remote Sensing, **3**: 302-310, April 2-7, 1989, Baltimore, Maryland.

Reboh, R. (l98l). "Knowledge engineering techniques and tools in the prospector environment." Technical Note 243, SRI International, Menlo Park, CA.

Reboh, R., Reiter, J., and Gaschnig, J. (l982). "Development of a knowledge based interface to a hydrological simulation program." SRI International, Menlo Park, CA.

Rinker, J., and P. Corl, 1984. Air Photo Analysis, Photo Interpretation Logic, and Feature Extraction, U.S. Army Corps of Engineers, Engineer Topographic Laboratories, Fort Belvoir, VA.

Ryerson, R. (1989): Image interpretation concerns for the 1990s and lessons from the past. - Photogrammetric Engineering and Remote Sensing **55**, 10: 1427-1430.

Sabins, Floyd. 1978. Remote Sensing: Principles and Interpretation.

Short, N. and R. Blair, eds., 1986. Geomorphology from Space: A Global Overview of Regional Landforms, U.S. Government Printing Office, Washington, D.C.

Short, N.M., P.D. Lowman Jr., S.C. Freden and W.A. Finch, Jr. 1976. Mission to Earth: Landsat Views the World. Washington, D.C.: NASA. [d]

Short, Nick. 1982. Landsat Tutorial Workbook: Basics of Satellite Remote Sensing.

Smith, Bill. 1977. Remote Sensing Applications for Mineral Exploration.

Strandberg, C., 1967. Aerial Discovery Manual, J. Wiley & Sons, New York.

Verstappen, H. Th. 1977. Remote Sensing in Geomorphology. Amsterdam: Elservier. [f/o]

Verstappen, H., 1977. Remote Sensing in Geomorphology, Elsevier, Amsterdam.

Way, D. (1978): Terrain analysis. - McGraw-Hill. New York.